BREAKTHROUGH INSTITUTE

TAKING INVENTORY OF CRITICAL MINERAL STOCKPILING: A SUPPLY CHAIN ANALYSIS

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EXECUTIVE SUMMARY

Historically, governments have established strategic reserves of key goods like oil, helium, and grain that can make purchases to keep essential industries afloat during volatile periods of low prices and sell stockpiled commodities to address shortages during times of crisis. With the Chinese government recently banning or tightening restrictions on numerous critical mineral exports to the United States,[1] national policymakers are increasingly turning to stockpiling as a potential insurance policy against mineral supply disruptions that could impact key U.S. industrial capabilities in the energy, semiconductor, space, metallurgical, and defense sectors.

On his first day in office and in his eighth executive order as a returning president, President Trump ordered the secretary of defense to review the posture and management of the National Defense Stockpile (NDS) "to ensure that the National Defense Stockpile will provide a robust supply of critical minerals in event of future shortfall."[2] Across the partisan aisle and months earlier during the 2024 presidential election, former Vice President Kamala Harris's campaign had pledged to "build a U.S. stockpile and create incentives to build out domestic processing capacity of critical minerals necessary for our economic and national security."[3]

Many proposals focus on the role of stockpiles as a tool to sustain essential industries through geopolitical upheaval. Numerous policy commentators[4] have pointed to the depletion of the NDS since the early 1990s as a critical vulnerability,[5] calling upon Congress to dramatically expand the NDS[6] to ensure supply coverage for a multi-year national emergency.[7]

Policymakers have also proposed ideas for a Strategic Resilience Reserve, which would reimagine the U.S. Strategic Petroleum Reserve (SPR) to support resilience, stability, and investment in key commodity markets.[8] This proposal would apply the Federal Reserve's framework to manage financial risk ex-ante and ex-post to target the vulnerabilities that stifle investment in commodity markets. Another Resilient Resource Reserve framework developed with industry consultation suggests a wholly-owned government corporation with the authority to take similar market actions.[9] Such a program could exist either in addition to or as an alternative to amassing minerals in an emergency stockpile similar to the NDS. Such proposals exhibit key differences from a simple, physical stockpile. Policymakers have described such a reserve program as aiming to "steady prices, protect consumers from price spikes, and generate stable revenue for producers during low-price periods."[10] Several proposed legislative bills, namely the Critical Materials Future Act[11] and the Securing Essential and Critical U.S. Resources and Elements (SECURE) Minerals Act,[12] call respectively for the establishment of a pilot-scale and full-size program. Such proposals chiefly emphasize the market certainty and investment de-risking benefits that a reserve program would provide to domestic mine and processing projects, with the accumulation of physical stocks of minerals primarily envisioned as a means to establish resilient markets and help self-finance the program rather than as a national emergency supply. In many cases, a reserve program might execute contracts that are of a financial nature only, without any direct physical offtake or storage of commodities.

In general, the U.S. faces daunting challenges to physical mineral stockpiling that severely limit the feasibility and efficacy of physical stockpiling as a solution to current critical mineral supply chain challenges. Downstream supply chain gaps in mineral processing and manufacturing of key technology components constrain the usefulness of physically stockpiling many raw materials. Meanwhile, current market and geopolitical conditions do not align well with ambitious efforts to accumulate stockpiles of many minerals. For example, the current stock of 14,000 kg of germanium metal in the NDS would only meet half a year of current U.S. consumption,[13] yet cannot be accumulated to a greater degree under the current Chinese export ban without dramatically exacerbating the supply shortage confronting the U.S. semiconductor sector. The NDS can neither statutorily serve private industry outside of an armed conflict, nor can it realistically meet U.S. advanced technology sector needs under most supply chain disruption scenarios.

U.S. critical mineral security ultimately requires broader industrial policy to develop projects that fill missing supply chain capabilities. Military needs may require targeted rejuvenation of the NDS, but such needs should not overly dictate the nation's wider mineral policy strategy. A U.S. strategic mineral reserve can provide valuable support for domestic supply chain development efforts by building markets and establishing clearinghouses for producers and offtakers; however, it should not seek to immediately accumulate physical mineral stockpiles sufficient for years-long crises as its principal objective. Rather, it is the acquisition of advanced supply chain capabilities that will heavily determine whether the United States can establish global technology leadership in key sectors like artificial intelligence, advanced computing, aerospace, and next-generation energy technologies.

Figure ES-1: Principles that inform policy decision-making on whether to accumulate a physical stockpile of a given critical material.

Chemical safety, stability, and purity:
- Is the material safe to store and shelf-stable over a year or longer?

Storage logistics:
- Is the material logistically and economically amenable to stockpiling?

Factors benefiting from expanded domestic industrial capacity

Ability to efficiently meet downstream demand:
- Can the U.S. use the material to produce advanced technologies?
- Does the material support co-production of other critical materials?

Trade and supply security characteristics:
- Can the U.S. reasonably accumulate the material in a stockpile?

Supply chain capabilities and ambitions:
- Does the U.S. mine a commodity or plan to?
- Does the U.S. possess–or seek to develop–downstream capabilities?

Key conclusions

- **Modern stockpiling is different from historical stockpiling.** Stockpiling efforts in the present day face pressure to serve a wider set of contingencies and purposes—targeted export bans, economic disruptions, commodity dumping onto global markets—than past strategic stockpiling programs narrowly defined to meet military-industrial needs in the event of war.
- **Most materials are not difficult to store.** Industry already handles most supply chain commodities in practice as part of normal business operations. Aside from impractical commodities like ore concentrates and lithium brines and unique exceptions such as highly reactive neodymium-boron rare earth alloys, a stockpiling program could feasibly store most materials for years by adopting common industry precautions.
- **Physical stockpiling may only rarely align with short-term national interests.** Near-term efforts to stockpile a mineral ideally require uncommon alignment of three factors:
    - Adequate downstream industrial capacity for processing or using a stockpiled material.
    - Favorable market conditions for acquiring sufficient material at a reasonable price and without exacerbating supply shortages.
    - Opportunity to purchase materials from—and thereby protect—upstream domestic producers of that commodity.

- **Ambitious physical stockpiles are a long-term project.** As popularly imagined, a national physical stockpile sufficient to support strategically critical U.S. industries and the U.S. military through a crisis lasting years may require as long as a decade to accumulate, along with significant expenditures that would, arguably, be better spent on developing supply chain capabilities.
- **The current national defense stockpile isn't the answer.** The NDS by its narrow statutory design does not have the flexibility or scale necessary to cover the needs of important U.S. economic sectors or to serve as a market actor that proactively buys and sells materials.
- **Physical stockpiling would not be the primary benefit from a new national mineral reserve.** The primary benefit of any new mineral reserve program would involve its role as a market actor for de-risking domestic mineral and processing projects through protections against dumping and price manipulation, rather than from the accumulation of physical reserves sufficient to, say, support the U.S. semiconductor or battery sectors through a period of crisis.
- **The U.S. needs to build projects more than it needs to build stockpiles.** Our analysis emphasizes how U.S. geologic resource constraints and supply chain bottlenecks in mining, processing, and manufacturing greatly complicate physical stockpiling efforts, highlighting the far higher importance of targeted industrial policy to fill gaps in domestic supply chain capabilities.

Recommended mineral supply chain stockpiling priorities:

Within all of the specific mineral supply chains analyzed, we identified the following commodities in each as the most theoretically suitable materials to prioritize, should a stockpiling program seek in principle to establish a physical reserve of that mineral:

- **Aluminum:** aluminum metal
- **Cadmium:** high-grade cadmium metal (99.999+%)
- **Chromium:** ferrochromium, chromium metal
- **Cobalt:** cobalt metal, cobalt sulfate
- **Copper:** refined copper metal
- **Gallium:** low-grade gallium metal (99.99%)
- **Germanium:** low-grade germanium metal (99.99%), germanium dioxide
- **Graphite:** natural graphite ore concentrate, synthetic graphite feedstock
- **Lithium:** hard rock lithium ore concentrates, lithium carbonate, lithium hydroxide
- **Magnesium:** magnesium metal, magnesium hydroxide

- **Manganese:** ferromanganese, silicomanganese, manganese sulfate
- **Nickel:** nickel sulfate, nickel metal, ferronickel
- **Rare earth elements:** hard rock ore concentrate, terbium oxide, dysprosium oxide, neodymium-praseodymium oxide
- **Tellurium:** high-grade tellurium metal (99.999+%)
- **Zinc:** zinc metal

INTRODUCTION

Energy and digital technologies have profoundly transformed since the onset of the 21st century, which in turn has altered the very foundations of modern society. The proliferation of digital electronics, development of wireless communications infrastructure, and explosive growth of advanced energy technologies are increasingly challenging manufacturers around the world to source growing quantities of raw materials key to these strategic economic sectors.

These economic and raw material trends are rewriting the global map of resource flows as countries begin actively surveying and accessing critical mineral deposits. Despite such growing interest in strategic minerals, today's advanced technologies continue to rely on mining and processing that are highly concentrated within just a handful of countries. Countries like the United States, Japan, and Korea produce cutting-edge end user products, but they control very little of the up- and mid-stream portions of supply chains upon which such industries rely.

Recent political momentum to secure critical mineral supply chains and reinvigorate American manufacturing calls for a more coherent national critical minerals strategy and accompanying supportive public policy. An effective national minerals strategy will require a wide range of policy efforts: infrastructure investments, international partnerships, targeted innovation in mining and metallurgy, regulatory reform, workforce training, geologic surveying, and market development efforts that encourage domestic and allied supply chain expansion and diversification.

Strategic stockpiling of critical minerals is one approach that could confer valuable long-term benefits to supply security. For American industries across supply chains, stockpiles of key raw materials could ensure security of supply for manufacturers in addition to protecting mining and refining projects from often volatile commodity markets by buying products. Broadly, stockpiling efforts can better ensure continued function of strategic industries during episodes of supply chain disruption or geopolitical crisis while promoting healthier growth of an American critical minerals sector.

However, the United States does not currently operate such a national public minerals stockpile or strategic reserve program, outside of the inflexible National Defense Stockpile (NDS), which can only release materials in the event of a military conflict. With the U.S. essentially contemplating the question of whether to restructure the NDS or develop a new stockpiling framework from scratch, policymakers must recognize that a mineral reserve program with the goal of accumulating and maintaining stockpiles capable of fulfilling economic or strategic industry needs during a long emergency would operate very differently from a mineral reserve program that prioritizes active market participation to insulate domestic producers from subsidized Chinese overproduction.

Indeed, the decision to establish a mineral reserve program must carefully account for the existing global supply chain picture, market dynamics, trade circumstances, and domestic industry capabilities for the commodities it might seek to prioritize. Such supply chain conditions substantially determine the set of feasible and infeasible outcomes, while significantly influencing the goals and structure of a mineral reserve program.

Table 1: Minerals assessed for this report, with listing status of each mineral on various international mineral commodity exchanges. More commodity exchange listings outside the Shanghai Metals Exchange (SHME) tend to suggest that a mineral is relatively more widely traded globally and benefits from a somewhat more diversified global supply chain. Major exchanges include London Metal Exchange (LME), Commodity Exchange (COMEX), New York Mercantile Exchange (NYMEX), Chicago Board of Trade (CBOT), Chicago Mercantile Exchange (CME), Tokyo Commodity Exchange (TOCOM), Shanghai Metals Exchange (SHME), and Shanghai Futures Exchange (SHFE).

	LME	COMEX	NYMEX	CBOT	CME	TOCOM	SHME	SHFE
Aluminum	x	x					x	x
Cadmium								
Chromium								
Cobalt	x	x					x	
Copper	x	x					x	x
Gallium							x	
Germanium								
Graphite								
Lithium	x	x					x	
Magnesium							x	
Manganese								
Nickel	x						x	x
Rare earth elements								
Tellurium								
Zinc	x						x	x

This report seeks to inform U.S. policy strategies on critical mineral stockpiling, while supplying potentially useful insights to other international governments and multilateral partnerships contemplating similar supply chain measures. We selected 15 strategically significant minerals for this assessment (Table 1), primarily focusing on minerals with valuable applications for advanced energy technologies and semiconductor manufacturing. Our list largely consists of federally designated critical minerals but also includes some non-critical minerals of interest. For each mineral supply chain, we mapped out the major production pathways including major commodities, intermediate products, and societal end uses. We assessed the stockpiling feasibility of each commodity within a given supply chain and then evaluated the particular suitability of that commodity for stockpiling within the context of current American industry capabilities and strategic circumstances. This report describes supply chain conditions, production pathways, and our recommendations for each mineral in its own mini-chapter and then synthesizes broader lessons and conclusions in a discussion section considering all these supply chains as a whole.

We gratefully thank and acknowledge numerous industry and academic contacts for providing expert feedback on this work as a whole.

These remain complex technical questions, and we anticipate the possibility—if not the eventuality—that technical specialists and industry stakeholders will respond to this report with constructive, critical feedback. Thus, we consider this to be the first version of our analysis, and we invite comments and suggestions from experts that will further strengthen this work. If such feedback proves substantial, we may publish an iterative future update that improves upon our synthesis of these industries.

OUR APPROACH: PRINCIPLES OF STRATEGIC STOCKPILING

In assessing each mineral supply chain, we consulted academic and industry literature, academic and industry experts, and open source information to evaluate the following five categories of stockpiling considerations.

Chemical safety, stability, and purity

- Vulnerability to chemical degradation
- Risk of contamination, if downstream material uses require certain thresholds of purity
- Vulnerability to physical attacks and cyber-attacks
- Probability and severity of chemical incidents (e.g., explosions, fires, leaks)

Storage logistics

- Specific volume, measured as volume per unit mass
- Form (e.g., powder, liquid, ingots, rolled sheets)

Ability to efficiently meet downstream demand

- Degree of additional processing required to synthesize final products
- Versatility for serving multiple end use markets/applications
- Relevance for technologies with salient economic and/or national security value
- Potential to support byproduct recovery of other critical minerals

Trade and supply security characteristics

- Frequency with which a material is currently traded, shipped, or stockpiled
- Import dependency and supply chain overconcentration
- Maturity and transparency of global markets that ensure robust price discovery for a commodity

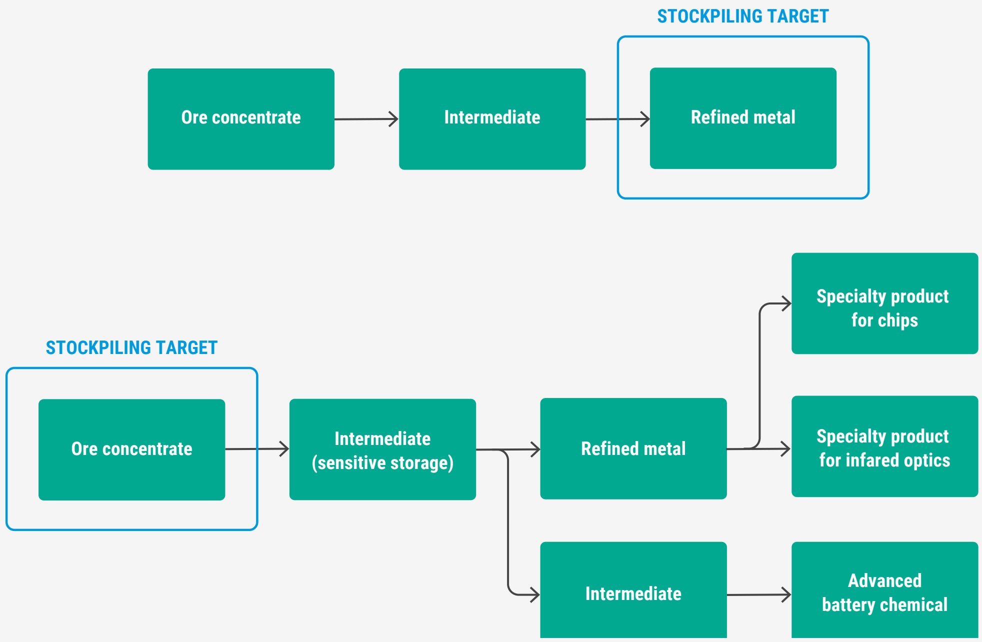
Compatibility with U.S. mineralogical and industrial assets

- Availability and composition of geologic resources
- Domestic extraction, processing, and refining capacity

We assessed the technical stockpiling feasibility of each commodity by considering only **Chemical safety, stability, and purity** and **Storage logistics**. The designation of **Feasible for stockpiling** therefore indicates that a compound's physical and chemical properties reasonably allow for long-term storage.

Our **Recommended Stockpile Priorities** for each mineral, by contrast, consider all five sets of strategic stockpiling considerations together. Our final recommendation stems from an evaluation of the relative benefits of every component of the supply chain with respect to the other stockpiling possibilities within the same mineral supply chain.

Figure 1: Examples of stockpiling prioritization. All else being equal, stable refined metals optimize the volume of material stored and support offtake for upstream producers while offering immediate usability in downstream industries. However, multiple competing downstream demand drivers may necessitate stockpiling of upstream commodities to serve a range of end use applications.



Aluminum (Al)

Recommended Stockpile Priority:
Aluminum metal

Summary:

- A strategic stockpiling program targeting aluminum should prioritize stockpiling of refined **aluminum metal** as opposed to upstream commodities like bauxite ore or alumina powder.
- All aluminum supply chain commodities exhibit relatively basic properties for safe bulk storage.
- It is impractical to stockpile millions of tons of aluminum to support economy-wide U.S. aluminum usage during a prolonged crisis.
- Aluminum metal stockpiling efforts should consider prioritizing a stock of high-purity aluminum for high-tech applications and should also leverage opportunities to accumulate recycled aluminum.
- Industrial policies should seek to facilitate new facility development and address the high energy costs and aging equipment of existing smelters.

Figure 2: Simplified aluminum supply chain with major commodities.

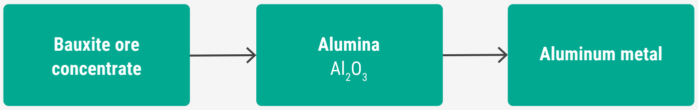


Table 2: Relevant aluminum supply chain commodities, with their characteristics and suitability for stockpiling. Green shaded row indicates this supply chain's recommended stockpile commodity.

Product	Feasible for stockpiling?	Advantages	Disadvantages	Additional Information
Bauxite ore concentrate	Yes	• Widely traded • Could double as gallium stockpile	• Large storage space • Dependent on two subsequent refining steps to produce aluminum metal	• The U.S. hosts minimal alumina refining capacity to process bauxite ore
Alumina	Yes	• Widely traded • Used in synthetic sapphire, battery separators	• Large storage space • Requires refining to produce aluminum metal	• Minimal U.S. bauxite mining and alumina refining would necessitate imports to build stockpiles
Aluminum metal	Yes	• Widely traded		• Plastic or paper used to separate sheets to prevent oxidation

Aluminum is the world's most extensively used light structural metal which gives it clear strategic importance. Modern societies use aluminum in vast quantities[14] in the automotive sector, containers and packaging, construction, consumer goods, electrical sector, and machinery. Most high-voltage transmission cables use a combination of braided aluminum and steel alloys. Solar farms and solar rooftop arrays often make extensive use of aluminum frames and racks.[15] Beyond these more ubiquitous uses of aluminum, advanced applications like defense, aerospace, electronics, batteries, and medical equipment require specialty aluminum at high purity levels that recycled aluminum cannot achieve.[16] Global growth in many of these sectors will likely drive sustained increase in aluminum demand, potentially between 3 and 5 million tons per year[17] by the U.S. energy and automobile sectors alone by the 2030s and 2040s. A robust aluminum recycling network will meet a considerable and growing fraction of needs over time. Substitution of magnesium metal for aluminum may also significantly influence future aluminum market trends. However, U.S. primary aluminum refinery production has fallen precipitously since the start of the 21st century, with only four remaining smelters running at reduced capacity and producing just 0.67 million tons of aluminum in 2024.[18] In total, foreign entities of concern control 65% of global primary aluminum production.

At the first step of the aluminum supply chain, mining operations extract aluminum-containing bauxite ore, typically from shallow near-surface deposits. Alumina refineries transform bauxite ore into aluminum oxide (alumina) using a set of chemical steps called the Bayer process.[19] Alumina production typically produces large quantities of bauxite residues—often colloquially referred to as "red mud"—as a hazardous byproduct.[20] Finally, aluminum smelters produce refined aluminum from alumina feedstock using the highly electricity-intensive Hall-Heroult process. Refining one ton of aluminum metal via the Hall-Heroult process typically requires 12,000-17,000 kWh of electricity.[21, 22]

All aluminum supply chain commodities—bauxite ore concentrate, alumina, and refined aluminum—boast simple storage characteristics and are already traded in large quantities globally. Aluminum metal sheets only require separation with oiled paper or plastic to prevent moisture entrapment and surface oxidation.[23] Bauxite ore can simply sit in covered piles, while alumina powder typically is stored in silos. Bauxite ores often contain trace amounts of gallium and serve as the primary source of global gallium production via alumina refinery facilities capable of performing byproduct gallium extraction.[24]

An ideal aluminum stockpile would be able to supply standard-grade metal for general consumer and manufacturing industries as well as military-grade, high-purity aluminum for defense, aerospace, and other specialized applications. These aims could be accomplished indirectly—by storing bauxite or alumina that is then upgraded into metal—or directly by stockpiling aluminum metal of varying grades.

With these goals in mind, a strategic stockpile prioritizing aluminum should accumulate refined aluminum metal. At present, the filling of U.S. stockpiles with bauxite ore, alumina, or high-purity aluminum metal would depend on foreign imports to some degree. Stockpiled bauxite and alumina also risk reliance on overseas refining facilities given insufficient domestic alumina production and declining aluminum smelter capacity. A stockpile of refined aluminum metal could also accommodate standard-grade aluminum metal sourced from recycled scrap. Aluminum recycling requires 95% less energy than primary production.[25] However, recycled aluminum cannot serve advanced technologies that require high-purity aluminum—a product that the U.S. no longer produces domestically since the suspension of operations at the Hawkesville smelter in Kentucky in 2022.[26]

Lessons Learned for Aluminum

Objectives: Presumably, U.S. aluminum stockpiling would prioritize meeting defense needs for high-purity aluminum and supporting continued operation for domestic aluminum smelters.

Assessment: It is impractical to stockpile millions of tons of aluminum to support economy-wide U.S. aluminum usage during a prolonged crisis. Purchase of just one million tons of standard-grade aluminum would require multiple billions of dollars, an expenditure likely sufficient to finance a new aluminum smelter with comparable annual production capacity. Industrial policies should seek to facilitate new facility development and address challenges existing smelters face from high energy costs and aging equipment.

Cadmium (Cd)

Recommended Stockpile Priority:
Cadmium metal

Summary:

- A stockpiling program seeking to accumulate cadmium should prioritize stockpiling **cadmium metal** as its primary commodity which enables flexible support for both nickel-cadmium batteries and thin film photovoltaic applications.
- Stockpiling the cadmium-bearing residues that result from zinc metal production could potentially offer an advantageous upstream feedstock material for cadmium, gallium, and/or germanium supply chains, depending on composition.
- Modest support for added cadmium byproduct recovery capabilities at zinc facilities in the U.S. and partner countries should generally resolve any future U.S. concerns regarding cadmium supply security.

Figure 3: Simplified cadmium supply chain with major commodities.

Table 3: Relevant cadmium supply chain commodities, with their characteristics and suitability for stockpiling. Green shaded row indicates this supply chain's recommended stockpile commodity.

Product	Feasible for stockpiling?	Advantages	Disadvantages	Additional Information
Zinc ore concentrate	Yes, with precautions	• Widely traded • Can also serve as zinc stockpile • May contain germanium, gallium	• Requires zinc processing and cadmium recovery capability • Flammability risk under certain air, temperature, and moisture conditions	• Sphalerite, for example
Zinc refinery residue	Yes	• May contain germanium, gallium	• Requires processing and cadmium recovery capability	• U.S. zinc refinery capacity with cadmium recovery currently limited to one facility
High-grade cadmium metal, Cd	Yes	• Downstream: minimal further processing needed for end uses	• Exposure to moisture can endanger further processing steps	
Cadmium telluride, CdTe	Yes	• Direct precursor of CdTe solar cells		

Though not officially a critical mineral,[27] cadmium has a few valuable high-tech industry applications. Nickel cadmium (NiCd) batteries[28] have lost market share to lithium ion batteries, but remain the biggest consumer of cadmium and are useful for industrial applications given their resilience in extreme conditions. Alloys, coatings, and pigments also drive industry demand for cadmium, along with some applications in X-ray[29] and infrared imaging devices.[30] Conventional pressurized water nuclear reactors use cadmium in fuel control rods, although not in significant quantities.[31] Cadmium also constitutes an essential component in cadmium telluride (CdTe) materials used in thin film photovoltaic systems. CdTe thin film photovoltaic systems constituted only 4% of the global photovoltaic market[32] in 2022, second to crystalline silicon. However, CdTe photovoltaics command a disproportionately high 16% share[33] of the U.S. utility-scale solar market. CdTe solar modules benefit from their streamlined manufacturing process, high shares of ex-China supply chain capacity, relatively energy-efficient manufacturing, high recyclability, and comparative advantages in dim light conditions. Scenarios for future U.S. cadmium usage in energy applications range between 170 and 650 tons of annual demand[34] in the 2030s and 2040s.

The cadmium supply chain largely depends on zinc production since cadmium does not occur in economically favorable concentrations by itself, while zinc ores such as sphalerite commonly contain trace amounts of cadmium. As such, zinc processing plants produce cadmium-bearing residues as a byproduct of converting zinc ore concentrates into zinc metal. Zinc metal production can occur at smelting plants or electrolytic refineries, but cadmium recovery mainly occurs at the latter. Facilities then leach the cadmium-bearing residue and deposit cadmium metal from the resulting solution. Meanwhile, CdTe production requires refining cadmium metal to at least 99.999% purity before incorporation into CdTe powders ready for thin film manufacturing.

Zinc refinery residues do not pose any particular storage concerns, while storage of zinc ore concentrates requires some precautions to minimize flammability-related risks under certain air, moisture, and temperature conditions. Furthermore, zinc ore concentrates represent a relatively dilute medium for cadmium storage. Given typical cadmium concentrations in zinc ore concentrate of 3500 ppm,[35] a 500,000 metric ton stockpile of zinc ore concentrate would only contain 1,750 tons of cadmium.

Of the cadmium compounds, storage of cadmium metal should protect the material from exposure to moisture, as moisture absorption could cause volatile reactions in further downstream processing. Storage and handling of cadmium compounds in general must observe basic industry precautions to manage toxicity risks.

A strategic reserve seeking to stockpile cadmium products should consider prioritizing cadmium metal as its primary commodity. Cadmium metal offers flexibility as a material for both NiCd battery, general industry, or CdTe photovoltaic applications and can be stored with moderate precautions. Zinc ore concentrates are widely available, but maintaining zinc ore stockpiles for their cadmium content requires substantial storage space and imposes storage-related risks while also depending on downstream zinc processing facilities' production of cadmium-bearing residues. Stockpiling cadmium-bearing residues directly would thus prove more advantageous than zinc ore concentrates. Used NiCd batteries could also serve as a source of cadmium[36] given established recycling practices and secondary markets.

Lessons Learned for Cadmium

Objectives: U.S. mineral stockpiling efforts likely would not prioritize cadmium, which faces lower supply risk.

Assessment: Cadmium production occurs via byproduct recovery during smelting of zinc ores. Modest support for added cadmium byproduct recovery capabilities at zinc facilities in the U.S. and partner countries should resolve any future concerns regarding cadmium supply security.

Chromium (Cr)

Recommended Stockpile Priorities:
Ferrochromium, chromium metal

Summary:

- A U.S. stockpiling program targeting chromium should prioritize stockpiling **ferrochromium and chromium metal** given the widespread applications of these commodities in steel and other alloys and the lack of U.S. production capacity.
- Current chromium defense stockpiles and chromium recycled via stainless steel are small relative to national consumption.
- Chromium-containing scrap can serve as a substitute for ferrochromium.
- Chromium is an example of a critical mineral for which the U.S. has little hope of ever establishing a domestic, vertically integrated supply chain due to limited geological resources and the absence of domestic mining or ferrochromium production capacity.

Figure 4: Simplified chromium supply chain with major commodities.

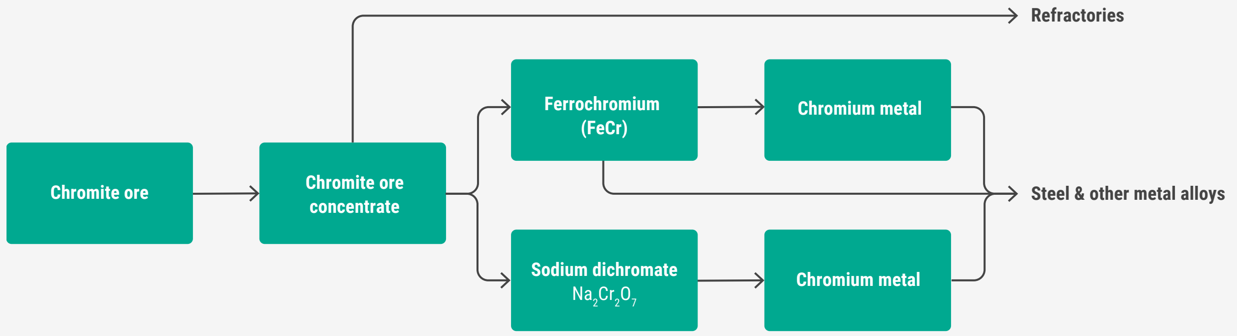


Table 4: Relevant chromium supply chain commodities, with their characteristics and suitability for stockpiling. Green shaded rows indicate this supply chain's recommended stockpile commodities.

Product	Feasible for stockpiling?	Advantages	Disadvantages	Additional Information
Chromite ore concentrate, $FeCr_2O_4$	Yes		• Large storage space	• Metallurgical grade ≥ 45% Cr_2O_3 • The U.S. does not mine chromite ore and possesses minimal reserves
Ferrochromium, FeCr	Yes	• Also serves as feedstock for Cr metal production	• Requires further processing to produce Cr metal	• Varies in composition from 45–95% Cr • The U.S. does not possess FeCr production capacity
Sodium dichromate, $Na_2Cr_2O_7$	Yes	• Feedstock for Cr metal production	• Feedstock material only with no direct uses • Oxidizer: avoid contact with combustibles	
Chromium metal, Cr	Yes	• Direct precursor for steel and other alloys		• 99.5-99.95% Cr for superalloys • ≥99.95% Cr for electronics • The U.S. does not possess Cr metal production capacity

Chromium constitutes an irreplaceable component in steel and other alloys, adding durability, temperature resistance, and anti-corrosion properties. The stainless steel industry[37] consumes roughly three-quarters of all chromium production in the form of ferrochromium (FeCr), though FeCr also sees minor use in other steels and alloys. Chromium metal also contributes to stainless steel production in addition to other alloys, platings, and advanced electronics. Superalloys used for specialty applications, such as in the aerospace or nuclear energy industries, require various combinations of low carbon FeCr[38] and high purity chromium metal.[39] Refractory materials used in industrial furnaces can also contain chromium. Though a negligible fraction of today's chromium market, iron redox flow batteries[40] used in long duration energy storage systems require chromium chloride. Estimates suggest steel alloys in the U.S. power and transportation sectors may consume 100-260 thousand tons of chromium annually[41] by the mid-2030s, relative to current national consumption of 300-440 thousand tons[42] per year. The NDS holds 50,000 tons of chromium products,[43] while the U.S. recycles around 100,000 tons of chromium contained in stainless steel scrap.

The chromium supply chain begins with mining the chromium ore chromite,[44] that is milled into an ore concentrate for further processing.[45] The production of FeCr requires smelting chromite ore concentrate to produce FeCr alloys with different chromium and carbon proportions. Electrolytic processing of FeCr produces chromium metal that can undergo further refining to achieve higher purities. Alternatively, facilities can produce chromium metal by first producing sodium dichromate (which itself serves as a reagent for various industries[46] such as pigments or wood preservatives) followed by aluminothermic processing to yield chromium metal.

Of the various chromium compounds, sodium dichromate requires some minor precautions to accommodate its reactivity. Other chromium compounds do not pose any particular storage difficulties.

A strategic reserve program targeting chromium should consider stockpiling FeCr and chromium metal as its primary commodities, since the U.S.[47] does not have the capacity to produce either material and these commodities carry importance for the steel and alloy industries. Storing chromium metal could also maintain a store of feedstock for manufacturing the chromium chloride used in specialty batteries. A strategic reserve should also consider stockpiling chromium-containing scrap[48] as such scrap can substitute for FeCr in various metallurgical applications. Recycled stainless steel, in fact, accounted for nearly a quarter of U.S. chromium consumption in 2024.

Lessons Learned for Chromium

Objectives: U.S. chromium stockpiling efforts would likely strive solely to accommodate national defense needs during a crisis scenario.

Assessment: Chromium is an example of a critical mineral for which the U.S. has little hope of ever establishing a domestic, vertically integrated supply chain due to limited geological resources and the absence of domestic mining or ferrochromium production capacity. Current chromium defense stockpiles and chromium recycled via stainless steel are small relative to national economy-wide consumption.

Cobalt (Co)

Recommended Stockpile Priorities:
Cobalt metal, cobalt sulfate

Summary:

- A cobalt stockpiling strategy should consider **cobalt metal and cobalt sulfate** in the short-term due to their advantageous supply chain positions and low storage-related risks.
- The ability of a cobalt stockpile to serve the cobalt metal market is especially important to downstream American industries, which currently consume more cobalt metal than any other cobalt chemical.
- In the long-term, adoption of requisite refining technologies and trade agreements with Indonesia and other laterite nickel ore producers could potentially make mixed nickel-cobalt hydroxide precipitate (MHP), mixed nickel-cobalt sulfide precipitate (MSP), and cobalt matte more feasible targets for cobalt stockpiling.
- Considering limited domestic cobalt deposits, policy support should overall aim to develop more cobalt processing and battery compound manufacturing capacity to fill gaps in U.S. supply chain capabilities, while exploring cooperation and investment to build cobalt supply chain projects in partner countries.

Figure 5: Simplified cobalt supply chains with major commodities.

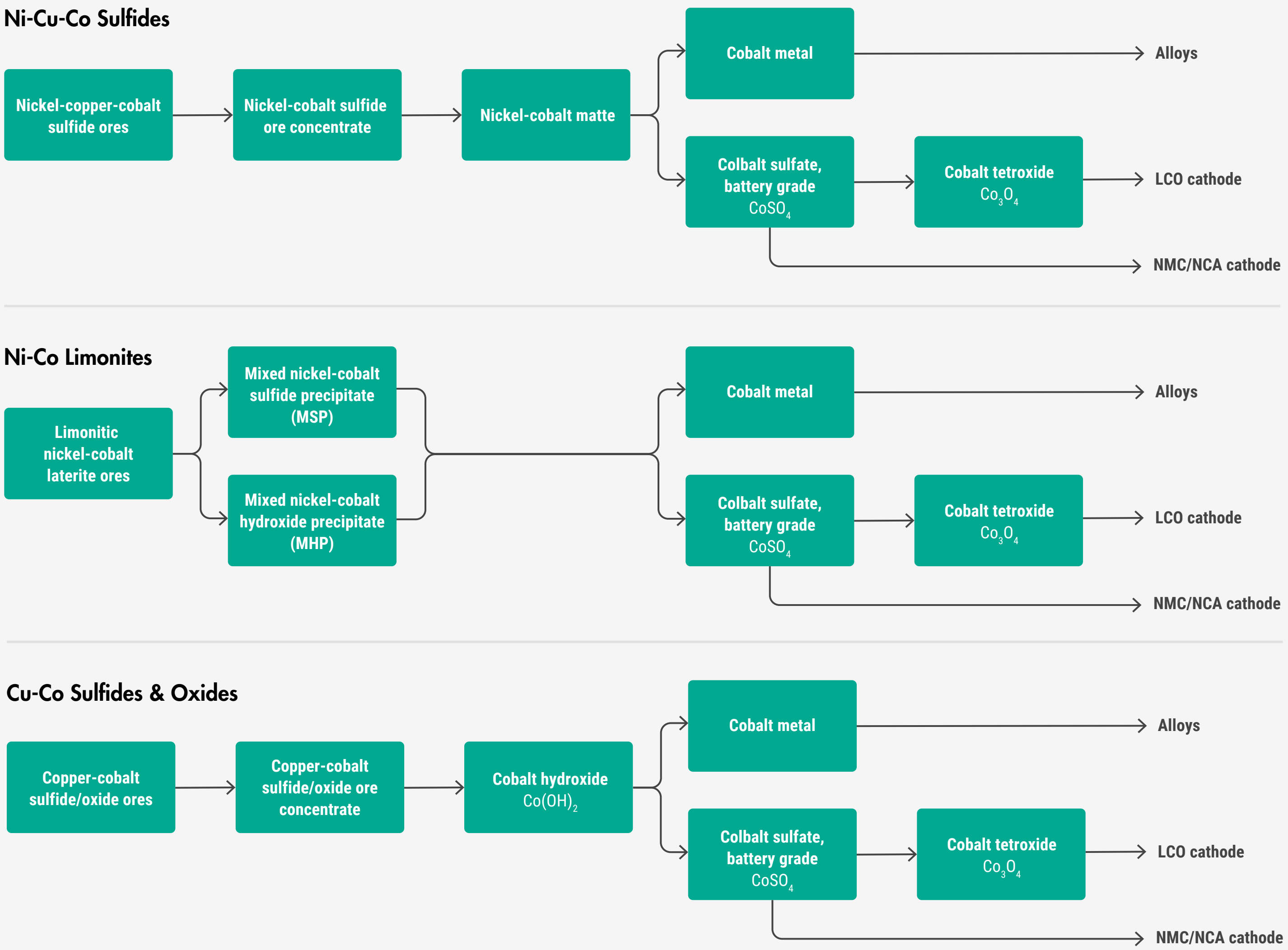


Table 5: Relevant cobalt supply chain commodities, with their characteristics and suitability for stockpiling. Green shaded rows indicate this supply chain's recommended stockpile commodities.

Product	Feasible for stockpiling?	Advantages	Disadvantages	Additional Information
Copper-cobalt sulfide/ oxide ore concentrate	No		• Large storage space	• The most commonly mined ore for cobalt production
Nickel-copper-cobalt sulfide ore concentrate	No		• Large storage space	
Cobalt hydroxide, $Co(OH)_2$	Yes	• Common precursor for all relevant cobalt compounds • Widely traded	• Requires additional processing to produce a marketable product	• Store as powder
Mixed nickel-cobalt sulfide precipitate (MSP)	Yes	• Precursor for all relevant cobalt compounds • Widely traded	• Currently a less common precursor for cobalt metal or sulfate	• All refining capacity is located in China
Mixed nickel-cobalt hydroxide precipitate (MHP)	Yes	• Precursor for all relevant cobalt compounds • Widely traded		• All refining capacity is located in China
Cobalt sulfate, $CoSO_4$	Yes	• Precursor for cobalt tetroxide • Directly used to make NMC and NCA battery cathode materials		
Cobalt metal	Yes	• Directly used in superalloys	• Serves separate supply chain branch from battery cathode market	
Cobalt tetroxide, Co_3O_4	Yes	• Directly used in LCO batteries	• Only currently serves LCO battery market	

Cobalt remains important in critical minerals discussions given its applications in the growing lithium-ion battery market and in advanced materials. Lithium-ion battery cathode materials drive the majority of global cobalt consumption. However, American manufacturing uses cobalt primarily in superalloys[49]—metals with high heat and stress resistance that are needed in jet engines, spacecrafts, nuclear reactors, and power plants. The primary cobalt-containing battery materials are lithium cobalt oxide (LCO), nickel manganese cobalt (NMC), and nickel cobalt aluminum oxide (NCA). LCO is mostly used for consumer electronics, while NMC and NCA are used mostly in electric vehicles and similar high-performance platforms like drones. Future U.S. battery applications alone may utilize 39 to 52 thousand tons of cobalt per year,[50] an order of magnitude greater than current total national consumption of 8500 tons per year.[51] Over 70%[52] of cobalt used in the U.S. is imported.

The cobalt supply chain is heavily concentrated in a handful of countries, raising price volatility and concerns over supply chain risks and bottlenecks. The Democratic Republic of the Congo (DRC) produces 70%[53] of the world's cobalt, though commercialization of new refining technologies in 2022 has significantly expanded[54] Indonesia's cobalt product output. China controls ~80%[55] of cobalt chemical refining to feed its prolific battery industry—a staggering degree of market control that may further increase, as growing Indonesian cobalt exports head almost exclusively[56] to China.

There is significant interest in supporting expansion and diversification of original equipment manufacturers given Chinese control over global battery production. Without alternative cobalt supply chains, however, China will continue to exert heavy influence over international patterns of electric vehicle adoption. Chinese supply chain risks are exacerbated by U.S. automakers' preference for NMC batteries over cobalt-free lithium iron phosphate (LFP) batteries (NMC batteries offer higher energy density and unlock more electric vehicle range—a critical factor for consumer acceptance in the U.S. market).

Many nickel refineries—such as those in Indonesia—also produce cobalt as a byproduct. The intermediates in these supply chains are stable and theoretically viable in a stockpile. However, the majority of global cobalt continues to originate from copper-cobalt ores in the DRC, while functionally all Indonesian cobalt is exported to China. We therefore focus our stockpiling strategy recommendations on the copper-cobalt supply chain.

Another potential source of a cobalt stockpile—alongside manganese, nickel, and copper—is in the form of seafloor polymetallic nodules. Nickel and cobalt prices together with manganese largely determine the economics of seafloor nodule collection, making nodules a reasonable medium for amassing a reserve of cobalt, depending on nodule composition. Industrial flowsheets for processing polymetallic nodules remain under development, but pyrometallurgical techniques[57] used to process saprolitic laterite ores can yield a nickel-cobalt-copper alloy,[58] which subsequent steps can convert to matte, then refine to isolate battery-grade cobalt sulfate. Other pathways[59] may chemically leach nodules to make mixed nickel-cobalt sulphide precipitate or a cobalt-molybdenum precipitate. A fleet of 10 production ships each collecting 3 million metric tons[60] of dry nodules per year would produce 51,000 tons of cobalt[61] annually assuming 85% cobalt recovery, enough to meet all future U.S. battery sector cobalt needs.

In principle, cobalt sulfate and cobalt metal would be the most strategic chemicals to stockpile given the relative immaturity of domestic cobalt refining and current state of the cobalt market. Cobalt sulfate is a heavily traded commodity, is chemically stable, and can directly serve battery manufacturers. With appropriate storage precautions, cobalt sulfate presents no salient safety concerns. The extensive use of cobalt metal in high-end American manufacturing applications makes cobalt metal stockpiling another well-advised choice for consideration. Planners should continue to monitor trends in the cobalt and battery markets to inform decision-making regarding any potential cobalt stockpiling strategy.

Lessons Learned for Cobalt

Objectives: Cobalt superalloys and battery packs key for defense technologies would probably be the priorities of U.S. stockpiling efforts targeting cobalt, with support for limited domestic cobalt mining as an additional goal.

Assessment: Current depressed prices and cobalt market oversupply[62] would align favorably with any near-term accumulation of physical cobalt reserves, which could in turn help U.S. producers secure offtake. However, bottlenecks in cobalt processing and battery component manufacturing complicate cobalt strategic stockpiling. Considering limited domestic cobalt deposits, policymaking should overall aim to develop more cobalt processing and battery compound manufacturing capacity to fill gaps in U.S. supply chain capabilities, while exploring cooperation and investment to build cobalt supply chain projects in partner countries.

Copper (Cu)

Recommended Stockpile Priority:
Refined copper metal

Summary:

- Copper is not a top priority for strategic stockpiling given its diverse sources of supply and a well-developed global market. It could be stored easily as **refined copper metal**.
- Bulk storage of copper commodities is simple with no special considerations required.
- Copper, while inconsistently listed as a critical mineral by various governments, should not be discounted entirely as a future stockpiling program target given considerable future demand growth and frequent geological co-occurrence with other critical minerals like nickel.
- Policymakers should consider supporting modernization of existing copper processing and refining capacity and new domestic copper project development.

Figure 6: Simplified copper supply chain with major commodities.

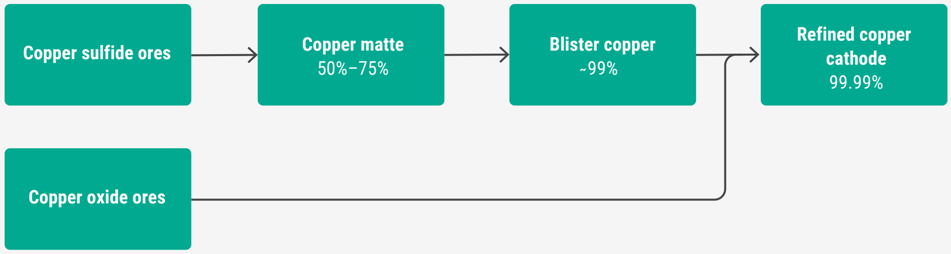


Table 6: Relevant copper supply chain commodities, with their characteristics and suitability for stockpiling. Green shaded row indicates this supply chain's recommended stockpile commodity.

Product	Feasible for stockpiling?	Advantages	Disadvantages	Additional Information
Copper sulfide/oxide ore concentrate	No		• Large storage space	
Copper matte	Yes	• Widely traded	• Large storage space • Stockpiling does not directly serve copper oxide route (~20% of world refined production)	
Blister copper	Yes	• Widely traded • Compact ingots easily stored	• Feedstock material only with no direct uses • Oxidizer: avoid contact with combustibles	
Refined copper metal (copper cathode)	Yes	• Widely traded • Compact sheets easily stored • Stockpiling serves both copper oxide and copper sulfide routes		• Significant global stocks and flows of recycled copper metal exist

Three-quarters[63] of copper consumption involves electrical uses, primarily[64] in the building, power, and transportation sectors. Most forecasts anticipate long-term growth in global copper demand driven by construction, energy, data centers, and infrastructure projects. Power sector and transportation sector usage of copper in the United States could grow to 1.1-1.6 million tons per year,[65] compared to total U.S. production of around 1.25 million tons in 2023.

Essentially all commodities throughout the copper supply chain are chemically stable with basic, straightforward storage characteristics. Mines produce either copper sulfide or copper oxide ores. Electrowinning directly produces refined copper metal (copper cathode) from copper oxide ores.[66] Copper sulfide ores, by contrast, typically undergo pyrometallurgical concentration at the mine site, with the ore concentrate then shipped to a smelter producing copper matte. Subsequent smelting operations convert copper matte into higher-purity blister copper, with further electrolytic refining producing refined copper metal.[67] Meanwhile, a significant secondary copper recycling market recirculates significant stocks of new copper from end-of-life scrap.

Like manganese, nickel, and cobalt, copper occurs in seafloor polymetallic nodules (around 1% copper[68] by mass) but contributes only on the order of 10% to the economics of seafloor nodule collection, making a stockpile of polymetallic nodules relatively impractical if prioritizing copper in isolation. Most proposed flowsheets for processing polymetallic nodules anticipate direct production of refined copper cathode sheets directly from a nodule-derived, copper-containing solution.[69] However, even a successful commercial nodule harvesting sector will exert a lower impact on large global copper markets relative to nickel, manganese, and cobalt. A sizeable fleet of 10 production ships each collecting 3 million metric tons[70] of dry nodules per year would produce 297,000 tons of copper annually assuming an 90% copper recovery rate, only equivalent to about 16.5% of U.S. copper consumption in 2024.

To minimize storage volume and to accommodate all copper production routes from copper oxide ores and copper sulfide ores (and potentially production from polymetallic nodules), refined copper cathode emerges as the logical choice for maintaining physical stocks of copper. Such copper metal stockpiling efforts should also seek to take advantage of the large recycled copper scrap market. Overall, however, copper does not presently constitute a top priority for strategic stockpiling given its diverse sources of supply and a well-developed global copper commodity market.

Lessons Learned for Copper

Objectives: Considering widespread copper use and re-use across the U.S. economy, national policy in a crisis scenario would likely simply redirect domestic material flows of copper to essential sectors rather than leveraging vast centrally accumulated stocks.

Assessment: Particularly compared to other minerals, the U.S. produces and recycles significant quantities of copper and enjoys a relatively diversified portfolio of copper imports. Steadily rising copper prices[71] would furthermore exacerbate the cost of accumulating a large national stockpile. Policymakers should consider supporting modernization of existing copper processing and refining capacity and new domestic copper project development.

Gallium (Ga)

Recommended Stockpile Priority:
Low-grade gallium metal (99.99%)

Summary:

- **Low-grade gallium metal (99.99%)** is the most attractive commodity in the gallium supply chain for storage in a national gallium stockpiling strategy. However, China's ban on gallium exports to the U.S. blocks any efforts to accumulate gallium stockpiles.
- Given gallium's production pathways as a co-product of alumina production and zinc refining, a strategic reserve program seeking to enhance gallium supply security should consider orienting stockpiling efforts to promote stable primary metal production (aluminum and zinc) necessary for byproduct recovery of gallium.
- Grant and financing support for investments in gallium byproduct recovery at facilities processing bauxite and zinc ores is also necessary to help establish gallium recovery capabilities in primary metal supply chains.
- Downstream gallium compounds pose challenging storage considerations due to gallium's reactivity.
- U.S. efforts should prioritize increasing gallium byproduct recovery and gallium refining capacity both domestically and in partner countries, including support for primary zinc and bauxite mining and refining as necessary.

Figure 7: Simplified bauxite-derived gallium supply chain with major commodities.

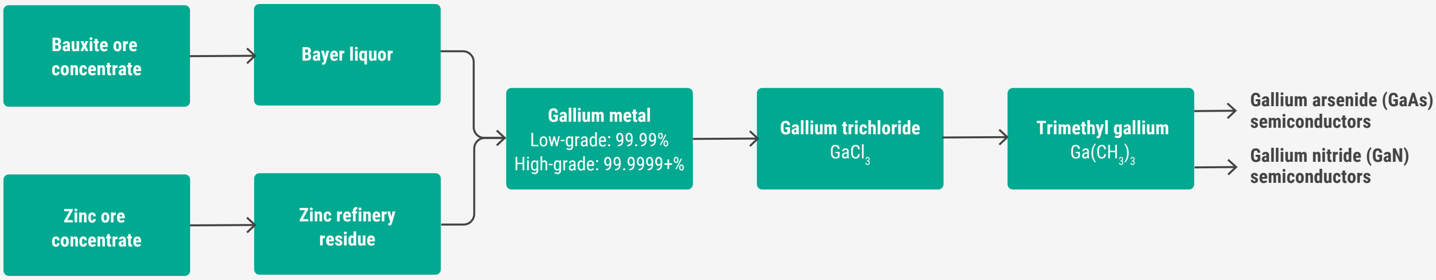


Table 7: Relevant gallium supply chain commodities, with their characteristics and suitability for stockpiling. Green shaded row indicates this supply chain's recommended stockpile commodity.

Product	Feasible for stockpiling?	Advantages	Disadvantages	Additional Information
Bauxite ore concentrate	Yes	• Stable • Can also serve as aluminum stockpile	• Large storage space • Requires bauxite processing and gallium recovery capability; gallium not immediately accessible	• U.S. bauxite contains too much silica for economical gallium extraction • U.S. has minimal alumina refining capacity to process bauxite ore
Bayer liquor	No		• Recirculated process liquid, not typically traded; unlikely to leave bauxite processing facility • Requires gallium recovery capability; gallium not immediately accessible • Highly hazardous	• Direct source of majority of current global gallium production
Zinc ore concentrate	No	• Stable • Can also serve as zinc stockpile • May contain germanium, cadmium	• Large storage space • Requires zinc processing and gallium recovery capability; gallium not immediately accessible • Flammability risk under certain air, temperature, and moisture conditions	• Uncommon gallium production route • Dependent on levels of gallium in ore
Zinc refinery residue	Yes	• Stable • May contain germanium, cadmium	• Large storage space • Requires zinc processing and gallium recovery capability; gallium not immediately accessible	• Uncommon gallium production route • U.S. zinc refineries produce residues, but are developing gallium extraction capacities and currently export residues for processing
Gallium metal	Yes	• Midstream: can support diverse/emerging uses and quickly meet market needs	• Liquid at 85F; requires temperature control	• Low-grade gallium (99.99%) must be intensively processed to high-purity gallium (99.9999+%) • Dissolves metals; store in plastic containers • Store in inert atmosphere
Gallium trichloride, $GaCl_3$	Yes, with precautions		• Corrosive solid • Reacts violently with water	• Store in inert atmosphere
Trimethyl gallium, $Ga(CH_3)_3$	Yes, with precautions	• Direct precursor for chips	• Liquid at room temperature; requires temperature control • May spontaneously combust when exposed to air	

Gallium serves as a key input in gallium arsenide (GaAs) and gallium nitride (GaN) integrated circuits and transistors, which see considerable use in electronics like semiconductor chips[72] and high-performance power electronics used in electricity grid switchgear and electric vehicles. Other semiconductors may utilize gallium oxide, while gallium also holds considerable importance for LED supply chains and for NdFeB rare earth magnets.[73] Integrated circuits made up 79% of domestic gallium consumption in 2024.[74] With increasing interest in GaN materials as a key technology for semiconductor innovation and as a power transistor in energy applications, gallium supply bottlenecks could pose a major obstacle for efforts to compete in these important advanced technologies. Gallium is particularly essential for satellite and space exploration technologies,[75] which make extensive use of gallium in gallium arsenide solar cells[76] and GaN power electronics.[77] The Chinese government's recent ban on gallium exports to the United States, cutting off the U.S. from a supplier producing 98% of the world's raw low-purity gallium,[78] has created an acute state of emergency across the global gallium value chain and downstream industries.

Currently, mining and metallurgical operations do not produce gallium as their primary marketable product, but rather as a byproduct of bauxite ore processing—one of the key early steps of aluminum production. When alumina producers produce alumina using the Bayer process, a subsequent set of techniques[79] allows for the extraction of gallium from the Bayer liquor.[80] Gallium can also be isolated as a byproduct from the residues of zinc electrolysis, but while some innovation efforts on such processes are underway, this production pathway currently accounts for a near-negligible share of global gallium production.

Any effort to stockpile gallium would need to overcome several daunting logistical and technical challenges. On one extreme, bauxite ore concentrate offers unambiguous chemical stability, but the low concentration of gallium (20-70 ppm)[81] would require logistical storage of around 300,000 to 1 million metric tons of bauxite ore concentrate to maintain a stock of gallium equivalent to one year of current U.S. consumption (20 tons). Furthermore, accessing the gallium contained in bauxite ore would necessitate Bayer process alumina production in a facility equipped to extract gallium as a co-product. Bauxite ore mined in the U.S. also typically contains higher silica content, making gallium recovery less economical.[82] On the other extreme, stockpiling pure gallium metal requires handling relatively little mass in theory (global production of 633 tons in 2023),[83] but demands storage in specialized containers filled with inert gas or under vacuum conditions due to gallium's reactivity. Such exacting storage requirements introduce considerable risk to any stockpiling program intended to hold gallium metal for weeks, months, or even years. Some industry publications suggest a shelf life of one year for gallium metal,[84] although other industry stakeholders assert that gallium can remain stable for longer than this if stored correctly.[85]

Meanwhile, zinc ore concentrates and zinc electrolysis residue contain gallium and could serve as a storage medium for gallium in the same way that bauxite ore concentrate could, complete with similar accompanying logistical difficulties. However, zinc ore concentrate carries some flammability risks under certain air, temperature, and moisture conditions. Furthermore, the zinc pathway for gallium stockpiling and co-production remains far less technologically developed at present. On the other hand, specific zinc ores such as U.S. deposits in Tennessee can also contain germanium and cadmium, introducing a potential to bank stocks of multiple critical minerals at once.[86]

Such practical and technical considerations help articulate a more indirect approach to developing and protecting gallium supply chain capacity. Secure supplies of gallium and similar byproduct critical minerals like germanium and cadmium ultimately depend on two factors: the market outlook for their primary metals, and the incentives for producers to invest in and maintain byproduct recovery capacity as part of downstream processing. Such business calculus will benefit the most from policy interventions that de-risk the primary market commodities—aluminum and zinc—and grants or financing support that specifically seek to establish byproduct recovery capabilities at processing facilities.

Lessons Learned for Gallium

Objectives: The conceivable goal of U.S. gallium stockpiling would be to meet defense sector and related semiconductor chip manufacturing needs during a supply shortage.

Assessment: Stockpiling would not help resolve U.S. gallium supply insecurity in the near to medium term. China's export ban has already imposed a supply emergency upon domestic consumers of gallium, and trying to build a stockpile would only hurt prices further and compete considerably with these critical industries. U.S. efforts should prioritize increasing gallium byproduct recovery and gallium refining capacity both domestically and in partner countries, including support for primary zinc and bauxite mining and refining as necessary.

Germanium (Ge)

Recommended Stockpile Priorities:

Low-grade germanium metal (99.99%), germanium dioxide

Summary:

- **Low-grade germanium metal (99.99%) and germanium dioxide** represent the most attractive commodities in the germanium supply chain for storage in a U.S. germanium stockpiling strategy. However, China's ban on germanium exports to the U.S. blocks any further efforts to accumulate germanium stockpiles.
- Long-term storage of refined germanium products is challenging due in part to their high purity requirements and structural fragility.
- Germanium chemicals used by industry are widely distributed throughout the supply chain, necessitating careful consideration of application-specific uses for different commodities, such as extensive consumption of germanium tetrachloride for high-speed fiber-optic cables.
- Germanium is optionally recovered as a byproduct of zinc refining, so a mineral strategic reserve program prioritizing germanium supply security should consider orienting stockpiling efforts to ensure stable primary zinc production.
- Grant and financing support for investments in germanium byproduct recovery at facilities processing zinc ores is also valuable for expanding germanium recovery capabilities.

Figure 8: Simplified germanium supply chain with major commodities.

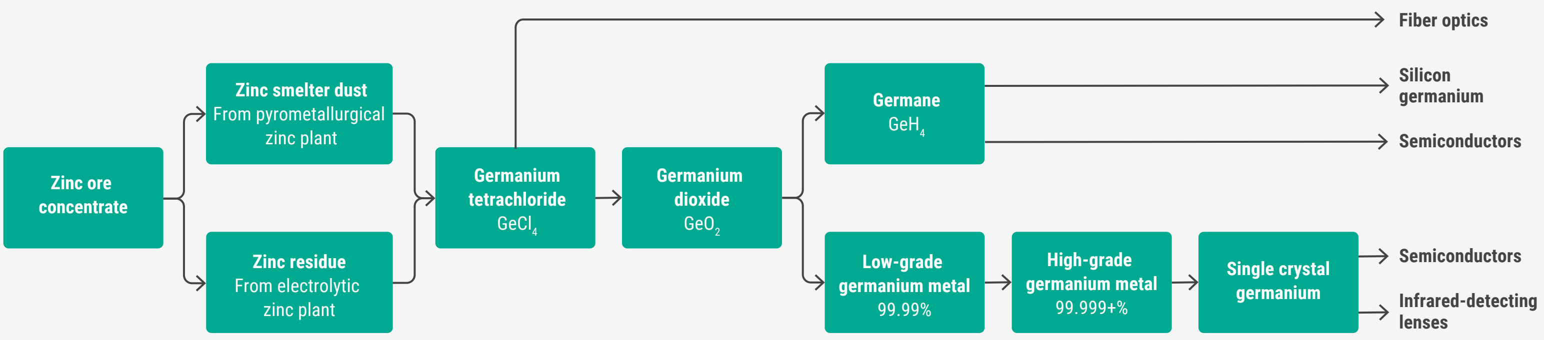


Table 8: Relevant germanium supply chain commodities, with their characteristics and suitability for stockpiling. Green shaded rows indicate this supply chain's recommended stockpile commodities.

Product	Feasible for stockpiling?	Advantages	Disadvantages	Additional Information
Zinc ore concentrate	No	• Stable, widely traded • Could also serve as zinc stockpile • May contain gallium, cadmium	• Requires zinc refining and germanium recovery; germanium not immediately accessible • Flammability risk under certain air, temperature, and moisture conditions	• Dependent on levels of germanium content in ore
Zinc smelter dust	No	• Germanium-bearing waste product	• Requires zinc pyrometallurgical refining and germanium recovery; germanium not immediately accessible	• The U.S. currently operates no pyrometallurgical zinc smelters
Zinc refinery residue	No	• Stable and already traded	• Requires zinc electrolytic refining and germanium recovery; germanium not immediately accessible • Potentially contains other hazardous compounds	• U.S. zinc refineries produce residues, but are still developing Ge extraction capacities and currently export residues for processing
Germanium tetrachloride, $GeCl_4$	Yes, with precautions	• Used in the biggest sector of Ge consumption (fiber optics) • Upstream feedstock for semiconductor applications	• Reactive, hazardous	• Corrosive to metals • Store in inert atmosphere
Germanium dioxide, GeO_2	Yes	• Can be used for both metal and germane production • Rapidly convertible to other products	• Feedstock material only with no direct uses	
Germane, GH_4	No	• Used directly to make semiconductors (e.g., silicon germanium)	• Non-versatile; used only for epitaxial layers (not all semiconductors) • Hazardous	• Store in pressurized cylinders and inert atmosphere • May spontaneously ignite upon contact with air
Low-grade germanium metal, 99.99%	Yes		• Feedstock material only with no direct uses	
High-grade germanium metal, 99.999+%	Yes	• Downstream; minimal further processing needed for end uses	• Non-versatile; only used for some semiconductors (as a substrate) and infrared lenses	• Slow oxidation occurs at room temperature; perhaps store in inert atmosphere
Single crystal germanium	No	• Directly used in semiconductors and other industries	• Non-versatile; only used for some semiconductors (as a substrate) and infrared lenses • Fragile	• Slow oxidation occurs at room temperature; perhaps store in inert atmosphere

Germanium-containing compounds are primarily used in advanced materials for the communications and electronics industries, particularly semiconductors. The market for germanium is expected to increase from $3.24 billion in 2023 to $4.5 billion in 2032,[87] driven by modern uses in data centers, artificial intelligence, 5G infrastructure, consumer electronics, and solar energy. As industrial and civilian reliance on these products continues to grow, so does the national importance of germanium.

The sectors that consume the most germanium in the U.S. are fiber optic cables (40%) and electronics (20%),[88] including some solar energy applications. Fiber optics use the unique refractive properties of germanium dioxide to decrease information loss over long ranges; however, manufacturers use germanium tetrachloride when synthesizing the cables. Examples of electronic products that contain germanium include semiconductor materials, cellular devices, radio systems for vehicles, and LEDs. Amorphous silicon germanium (a-SiGe) thin-film photovoltaics also use germanium, though they capture only a small fraction of the overall photovoltaics market. Other notable technologies that use germanium include infrared lenses for thermal cameras/night vision goggles and a catalyst for making PET plastic. These applications make up large shares of global germanium consumption, with infrared lenses particularly important for widely issued U.S. military equipment.

Zinc ores containing germanium contain only trace amounts of the element (50 to 400 ppm[89])—too little for direct germanium extraction to be economical or for zinc ore concentrate to be practical as a stockpiling medium for germanium. Instead, primary germanium is produced as a byproduct of the zinc metal industry, either from zinc flue dust (dust produced from zinc smelting) or zinc residue (the material remaining after electrolytic zinc production). The United States currently performs no primary germanium extraction[90] via either pathway; however, American zinc refineries *do* produce germanium-containing zinc residues that are exported for germanium recovery. After largely undergoing refining abroad, the U.S. imports most of its germanium tetrachloride, germanium dioxide, and germanium metal.

Germanium tetrachloride, dioxide, and metal can all be processed into ultra high-grade germanium metal (99.9999+%) for electronics. The techniques to achieve such high purities require precise manufacturing, often performed at lab scales in controlled environments (e.g., clean rooms). Manufacturers melt the extremely pure metal, then use a "seed" germanium metal crystal to guide a slow cooling. The final product has a uniform, crystalline atomic structure that matches that of the seed crystal. Recovery of germanium from used electronic scrap is possible and occurs in the U.S. at a single refinery that recycles germanium from scrap to make germanium tetrachloride.

The germanium supply chain faces substantial ongoing risks. Few countries[91] produce or recycle germanium, and over 60%[92] of germanium refining is controlled by China, which has recently restricted germanium exports to the United States. The remaining production occurs in the U.S., Belgium, Canada, Germany, and Russia,[93] though Japan and Ukraine[94] have historically produced germanium products. Moreover, germanium's importance to American industry will increase as U.S. technology sectors continue to grow. The U.S. National Defense Stockpile contained at least 14 tons of germanium metal and just under 7 tons of germanium scrap as of late 2022.[95]

From a stockpiling perspective, germanium tetrachloride is well positioned in the supply chain as the germanium compound used for fiber optics and an intermediate for other germanium compounds. However, germanium tetrachloride exhibits hazardous chemical properties including metal corrosion, toxicity, and reactivity with water. Strict adherence to chemical safety procedures would minimize the risk of long-term germanium tetrachloride storage. Nevertheless, we do not recommend germanium tetrachloride for stockpiling, as the ability to additionally serve fiber optic manufacturers does not warrant the risks associated with storing this volatile compound.

Neither germanium dioxide nor germanium metal have direct industrial applications, but may warrant consideration for stockpiling efforts due to their positioning in the germanium supply chain. Storing either commodity would allow the stockpile to serve the needs of multiple industries with no extraneous storage precautions and minimal additional processing required to achieve a marketable product.

As is the case for other critical minerals like gallium that originate from byproduct recovery, a secure germanium supply chain pivotally depends on a stable zinc market and domestic zinc production, as well as the development of germanium recovery capabilities at zinc processing plants.

Lessons Learned for Germanium

Objectives: As in the case of gallium, U.S. germanium stockpiling would strive to cover defense sector and related semiconductor chip manufacturing needs during a supply shortage.

Assessment: The NDS does contain limited stocks of germanium equivalent to about half a year of current U.S. consumption,[96] and many industry actors maintain private stockpiles. However, China's ban on germanium exports to the U.S. blocks any further efforts to accumulate germanium stockpiles. U.S. efforts should prioritize developing new germanium byproduct recovery and germanium refining capacity both domestically and in partner countries, including support for primary zinc and mining and refining as necessary.

Graphite

Recommended Stockpile Priorities:
Natural graphite ore concentrate, synthetic graphite feedstock

Summary:

- We suggest that a stockpile program focusing on graphite should select **flake size sorted natural graphite ore concentrates and synthetic graphite feedstock** as its primary commodities for storage and exchange.
- Most graphite feedstocks and products possess relatively favorable storage characteristics.
- Flake size sorted graphite ore concentrate has the advantages of easily managed storage and flexible suitability for many downstream applications. Subsequent products offer less versatility once they have been reshaped or carbon-coated, although **upgraded uncoated spherical graphite for high-end applications** may also warrant limited stockpiling.
- Stockpile accumulation of graphite could support essential battery production and metallurgical sector needs for national defense, while strengthening the business case for U.S. graphite projects currently under development.
- Stockpiling efforts would not obviate the need for other policy support to advance domestic project development—including synthetic graphite operations—and grow downstream graphite supply chain capabilities.

Figure 9: Simplified graphite supply chains with major commodities.

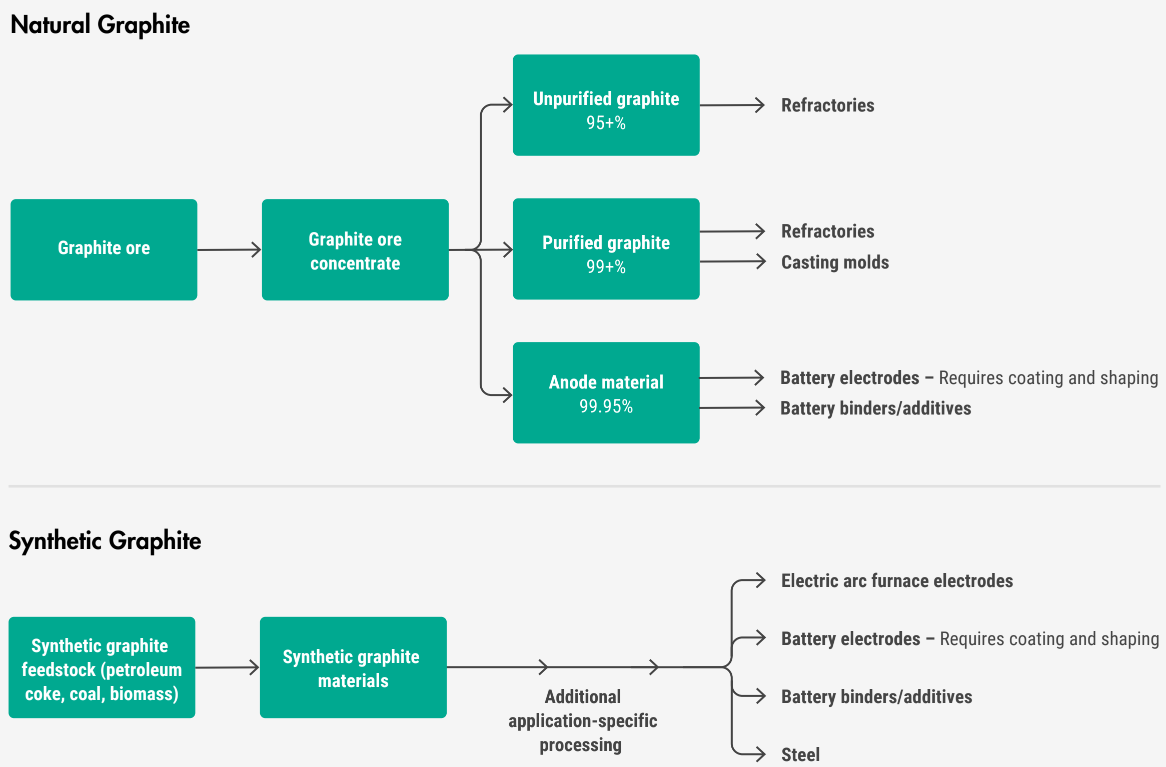


Table 9: Relevant graphite supply chain commodities, with their characteristics and suitability for stockpiling. Green shaded rows indicate this supply chain's recommended stockpile commodities.

Product	Feasible for stockpiling?	Advantages	Disadvantages	Additional Information
Graphite ore concentrate	Yes	• Can be selectively purified according to market demand		• Processed graphite is often sorted into different grain/mesh sizes, while finished products may be spheroidized and carbon coated • Spherical graphite may unroll back into powder if disturbed regularly • The U.S. does not currently mine graphite ore and has limited reserves, but is developing some new mine projects
Synthetic graphite feedstock (petroleum coke, coal, biomass)	Yes	• Higher performance for high-end products • Essential for specialized electronic and telecommunications applications	• More expensive to produce	
Unpurified graphite, 95+%	Yes			
Purified graphite, 99+%	Yes	• Can also be used for unpurified graphite products • Supports both natural and synthetic graphite production routes		
Graphite anode material, 99.95+%	No	• Only purity of graphite acceptable for use in advanced technologies	• Non-versatile: products are specialized for individual customers	

High-purity graphite remains the primary material of choice for lithium-ion battery anodes, with the global battery sector consuming a large fraction—over 36%[97]—of yearly graphite production at present. The battery sector's share of the global graphite market may grow to 78% by 2035.[98] Outside the battery sector, relatively low-quality graphite electrodes see high-volume use in a variety of metallurgical sector processes like electric arc furnace steelmaking and aluminum smelting. Previous Breakthrough Institute modeling suggests that future U.S. energy and transportation sector battery deployment could demand 1 million to 1.5 million tons of battery graphite per year by the mid-2030s, growing 16 to 25 times relative to current U.S. transportation sector usage.[99] Graphite consequently has strategic importance for advanced energy technologies, metal production, and the defense industry.

The graphite supply chain is relatively simple compared to many other critical mineral production pathways. Mining operations extract graphite from deposits and perform initial crushing and processing,[100] then sell the resulting graphite ore concentrate to downstream processing facilities. Those processing operations may further purify the graphite material, physically grind it into finer grain sizes, perform spheroidization, and/or chemically coat the particles.[101] Alternatively, the production of synthetic graphite does not require mining, instead converting a carbon-rich feedstock (e.g., petroleum coke, coal, biomass) into graphite material. This process yields a higher-purity product and enables better performance as a battery material. However, synthetic graphite production carries higher costs and requires considerably more input electricity compared to the already energy-intensive processing and purification of natural graphite ore concentrate. In 2022, average synthetic graphite prices remained 3.7 times that of natural graphite.[102]

Most graphite supply chain commodities do not pose any particularly difficult storage implications or safety risks.[103,104] Consequently, graphite materials align quite favorably with the practical considerations for stockpiling.

Typical graphite ore concentrate already possesses a purity of 90-95% graphite by mass,[105] such that a ton of graphite ore concentrate would theoretically suffice for the production of around 11-12 light-duty electric vehicles,[106] not counting losses in subsequent processing steps. Graphite ore concentrate has historically sold in North America at prices of $400 to $2000 per ton depending on flake size and purity,[107] with the caveat that such prices remain acutely sensitive to the highly overconcentrated Chinese graphite market. Together, these characteristics suggest that graphite ore concentrate can perform adequately as a medium for commodity market liquidity and exchange.

Battery market growth suggests that graphite will soon become a commodity traded in relatively large volumes of millions of tons annually. A strategic reserve of sufficient scale to ensure offtake for a handful of graphite mining operations (assuming production on the order of 60,000 tons/yr per mine)[108] and influence global graphite market dynamics would require significant logistical scale and costs. Such a program would likely need to physically receive and store potentially a couple of hundred thousand tons of material each year.

Downstream manufacturers often employ proprietary coating techniques to coat spherical graphite based on their particular technical requirements. Consequently, limited stockpiles of uncoated spherical graphite can convey strategic advantages by maintaining ready reserves of high-quality processed material that require only specialized coating for downstream industry use. Industry feedback suggests that stocks of D50 spherical graphite in the 8-10μm and 16-18μm size ranges would serve a meaningful range of high-end manufacturing needs.[109]

A strategic reserve program seeking to include graphite should keep several unique graphite supply chain considerations in mind. First, not all graphite materials are created equal, and a reserve program should logically prioritize high-value graphite materials for batteries, electronics, aerospace, and similar applications over low-value smaller flake or amorphous graphite consumed in aluminum or steel production. Second, stockpiling efforts may need to categorize products by flake size, which poses some implications for which downstream applications can use a given material.

A coarse grain fraction (+80 Mesh 95% carbon) and a fine grain fraction (-140 Mesh, 95% carbon) could cover most needs and applications, particularly if additionally supplemented by stocks of uncoated spherical graphite products. Third, such a program should ideally handle graphite raw material produced from both natural graphite mines as well as synthetic graphite operations, in order to provide both production pathways with the same offtake and price stability benefits.

Lessons Learned for Graphite

Objectives: Presumably, graphite stockpiling efforts would aim to support essential battery production and metallurgical sector needs for national defense, while also supporting domestic graphite projects.

Assessment: Current global graphite market oversupply and low prices[110] would favor stockpile accumulation of graphite, while helping strengthen the business case for the handful of U.S. graphite projects currently under development. However, tightening Chinese scrutiny of graphite exports to the U.S. could constrict further in response to any efforts to make graphite purchases with the goal of building a strategic stockpile. Furthermore, geological assessments suggest domestic graphite deposits preclude the U.S. from becoming a major global natural graphite producer,[111] while limited operating graphite processing and graphite battery anode production capacity also pose challenges. Stockpiling efforts would not obviate the need for other policy support to advance domestic project development—including synthetic graphite operations—and grow downstream graphite supply chain capabilities.

Lithium (Li)

Recommended Stockpile Priorities:

Hard rock lithium ore concentrates, lithium carbonate, lithium hydroxide

Summary:

- We suggest that any U.S. lithium stockpiling efforts focus on **hard rock lithium ore concentrates (e.g., spodumene), technical-grade lithium carbonate, and technical-grade lithium hydroxide**.
- Stockpiling of lithium ore concentrates would benefit from ore's long-term stability, while helping to maintain domestic lithium mining by building the stockpile during periods of market oversupply; but it would face challenges from current bottlenecks in domestic downstream ore-processing capacity.
- A lithium stockpiling program should consider shifts in market trends that warrant storing different amounts of lithium carbonate for LFP batteries versus lithium hydroxide for NMC batteries.
- Dedicated storage facilities for lithium hydroxide and lithium carbonate may need to cycle material more quickly to minimize risk of degradation, which increases beyond six months for hydroxide and beyond two years for carbonate.

Figure 10: Simplified lithium supply chains with major commodities.

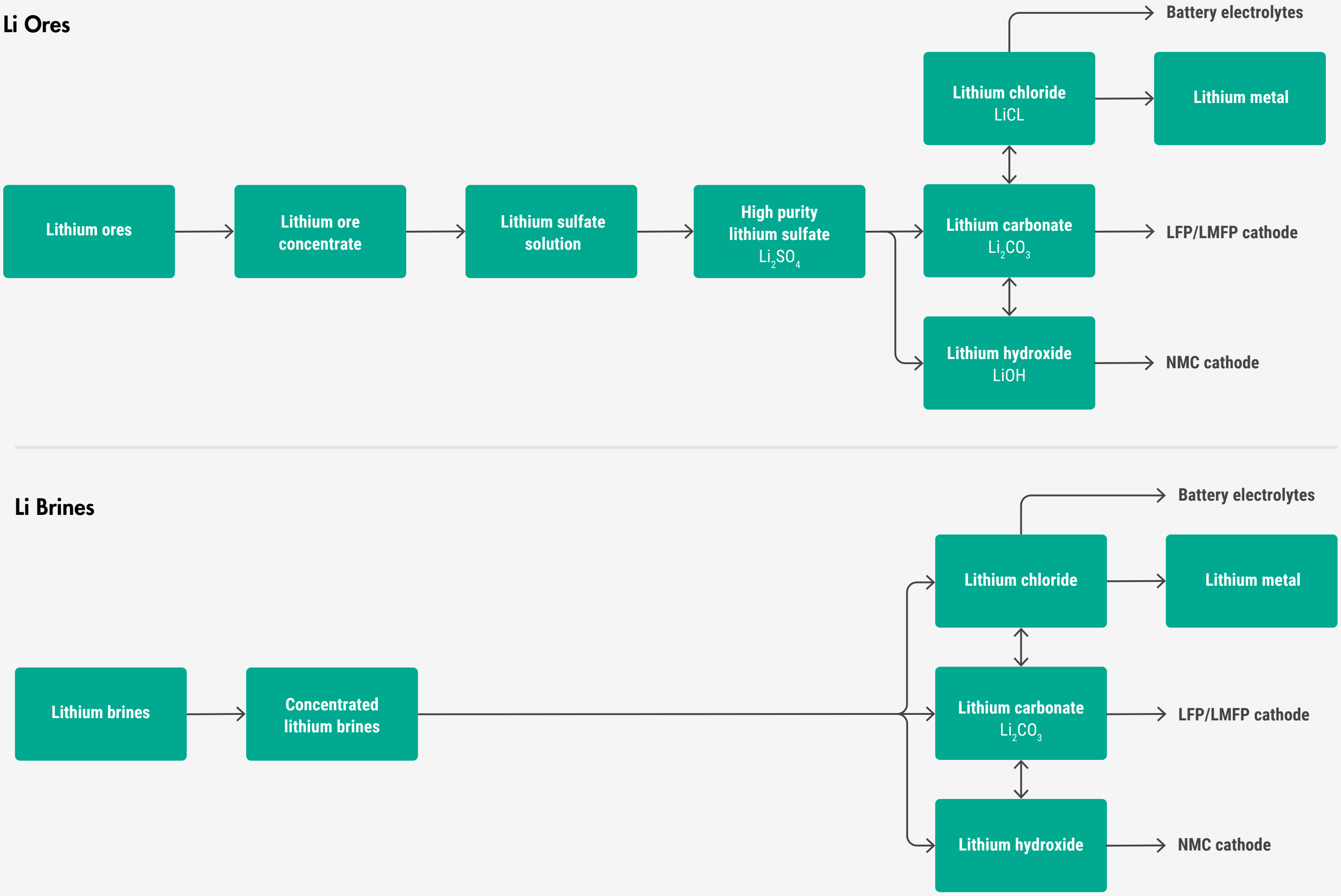


Table 10: Relevant lithium supply chain commodities, with their characteristics and suitability for stockpiling. Green shaded rows indicate this supply chain's recommended stockpile commodities.

Product	Feasible for stockpiling?	Advantages	Disadvantages	Additional Information
Concentrated brines	No		• Not typically traded • Impractical storage volumes • Risk of contamination	• Facilities often consume brine on-site for further processing
Lithium ore concentrates	Yes	• Low-cost feedstock for downstream products	• Requires further processing into downstream products • Large storage space	• Spodumene, petalite, and lepidolite, for example • Reactive to moisture • The U.S. is currently building and developing its first mine projects and processing facilities
Lithium sulfate, Li_2SO_4	Yes	• Stable long-term • Feedstock for producing both lithium carbonate and lithium hydroxide	• Requires further processing into downstream products • Not commonly traded; not typically transported outside lithium processing facility	• Intermediate product of ore processing • Absorbs water vapor from air
Lithium carbonate, Li_2CO_3	Yes	• Stable within a couple of years; can be reprocessed anew if degraded • Growing market demand for LFP batteries	• Demand may shift depending on battery market trends	• Absorbs water vapor from air
Lithium hydroxide, LiOH	Yes, with precautions	• Stable within 6–12 months; can be reprocessed anew if degraded • Strong market demand for NMC batteries	• Demand may shift depending on battery market trends • Reacts with atmospheric CO_2; risk of degradation in long-term storage	• Absorbs water vapor from air • Stockpile must cycle regularly to reduce degradation risk
Lithium chloride, LiCl	No	• Stable long term • Precursor for lithium metal and battery electrolytes • Output of direct lithium extraction process, convertible to lithium carbonate or lithium hydroxide	• Limited niche market for lithium metal • Requires further processing into downstream products • Not commonly traded • May not be transported outside direct lithium extraction facility • Direct lithium extraction processes are evolving	• Absorbs water vapor from air
Lithium metal	No	• Possible emerging use as battery anode material.	• Limited niche market for lithium metal • Impractical to store and potentially dangerous	• Highly reactive, requires storage in inert gas or oil

Lithium is essential for the function of lithium-ion batteries, with the movement of lithium ions between the battery anode and cathode directly responsible for inducing an electrical flow. Important lithium materials include lithium carbonate as a precursor for lithium-iron phosphate (LFP)[112] and lithium manganese iron phosphate (LMFP) battery cathode materials and lithium hydroxide as a precursor for nickel manganese cobalt (NMC)[113] battery cathode materials. A typical passenger electric vehicle with a 75 kWh battery pack will require around 6 to 9 kg of lithium content in total. Some nascent next-generation battery chemistries not yet commercialized are exploring the use of lithium metal as the battery anode,[114] potentially unlocking vast improvements in energy density. Some lithium-free battery chemistries like sodium-ion batteries have entered the commercial market, but come with their own trade-offs like lower energy density. Future U.S. battery demand in the electricity grid and vehicle applications could require the equivalent of 100,000 to 150,000 tons of lithium annually.[115]

The lithium supply chain branches from two dominant sources[116] of raw lithium: continental brines and hard rock ores. Continental brine operations pump mineral-rich groundwater to surface ponds where evaporation increases the lithium concentration over a period of up to two years.[117] On-site facilities can process the concentrated brine into lithium carbonate, lithium chloride, or lithium hydroxide,[118] and separate facilities can further process the lithium chloride into lithium metal.[119] Alternatively, hard rock operations largely mine the mineral spodumene and, to lesser extents, petalite and lepidolite. After excavation, mines mill the raw ore to produce an ore concentrate. A separate facility will traditionally convert the concentrate to lithium sulfate, which undergoes further processing into either lithium carbonate or lithium hydroxide.[120] Finally, direct lithium extraction from subsurface brines first produces lithium chloride, which subsequent processing converts into either lithium carbonate or lithium hydroxide.[121]

Ore concentrates pose no particular storage difficulties and offer a more practical option[122] for stockpiling upstream lithium materials than brines, which would require larger volumes, extra precautions to prevent contamination, and potentially specialized infrastructure. A stockpiling program may also struggle to secure sufficient supplies of brine since many facilities do not sell brine and instead process it on-site into downstream products.

The intermediate products—lithium sulfate, carbonate, hydroxide, and chloride—largely do not pose any difficult storage requirements. Lithium carbonate and lithium hydroxide offer particular advantages given their direct application to batteries. Lithium carbonate is highly stable for around two years and can be reprocessed anew to generate fresh lithium carbonate if the material has degraded. However, lithium hydroxide stored over long periods may decompose and react with atmospheric CO_2, with suppliers often recommending a shelf life of between six months and two years.[123] As such, any operations stockpiling lithium hydroxide may need to cycle the material more frequently to minimize risk of degradation. Given potential degradation concerns, stockpiling of technical-grade lithium carbonate and lithium hydroxide may prove more economic than stockpiling these compounds at battery-grade quality.

Stockpiling lithium sulfate offers minimal benefits as it requires further processing to yield lithium carbonate or hydroxide and since facilities often fully process ore concentrates without selling the lithium sulfate intermediate on the market. As for lithium metal, stockpiling is feasible but requires special precautions such as storage in inert gases or oils. Such unique considerations make stockpiling its precursor material, lithium chloride, preferable should demand for lithium metal anodes increase in the future, particularly if direct lithium extraction techniques scale dramatically moving forward.

China[124] dominates lithium ore concentrate processing, importing nearly all the spodumene from the world's largest lithium producer, Australia.[125] Stockpiling ore concentrates could prove useful for de-risking U.S. hard rock lithium mine projects by ensuring offtake. Note that hard rock lithium mines operate under more marginal economics[126] than brine facilities and thus carry more risk of closure should lithium prices drop. In the short term, such risks could justify including ore concentrates in a strategic reserve, while developing diversified hard rock lithium-processing capacity in the U.S. and elsewhere. In the long term, however, emerging processing techniques collectively referred to as direct lithium extraction[127] could render brine operations even more competitive and eventually move industry away from hard rock mining. Stockpiling lithium carbonate and lithium hydroxide would balance this risk, keeping in mind that appropriate amounts of either must also consider shifts in demand for different battery types. Ultimately, companies and commodity traders may use one commodity's price to hedge contracts[128] trading in other commodities, so a stockpiling program targeting one lithium commodity may also help develop more mature markets for the others.

Lessons Learned for Lithium

Objectives: Domestic lithium stockpiling would prioritize essential battery production for national defense during a crisis scenario, while also providing additional offtake assurance for domestic lithium projects.

Assessment: The lithium market is also currently confronting low prices potentially amenable to stockpile accumulation.[129] Establishing a lithium reserve could also significantly bolster U.S. efforts to become a major player in global lithium production by leveraging significant domestic hardrock and brine lithium deposits. However, the U.S. lithium supply chain lacks adequate downstream capacity to produce battery-grade lithium chemicals, particularly from hardrock lithium ores like spodumene, underlining the value of targeted support for downstream refining.

Magnesium (Mg)

Recommended Stockpile Priorities:
Magnesium metal, magnesium hydroxide

Summary:

- A stockpiling program targeting magnesium should focus on **magnesium metal and magnesium hydroxide** to best serve both the magnesium and magnesia industries while minimizing storage hazards.
- A magnesium stockpiling strategy faces obstacles from limited American supply chain capacity, the reactivity of some magnesium compounds, and the divergent supply chains of magnesium metal and magnesia.
- A prescient U.S. critical minerals strategy might arguably prioritize expanding magnesium production domestically and in partner countries, focusing primarily on magnesium production from brines, given the high energy requirement of producing magnesium metal from magnesium hardrock ores.

Figure 11: Simplified magnesium supply chains with major commodities.

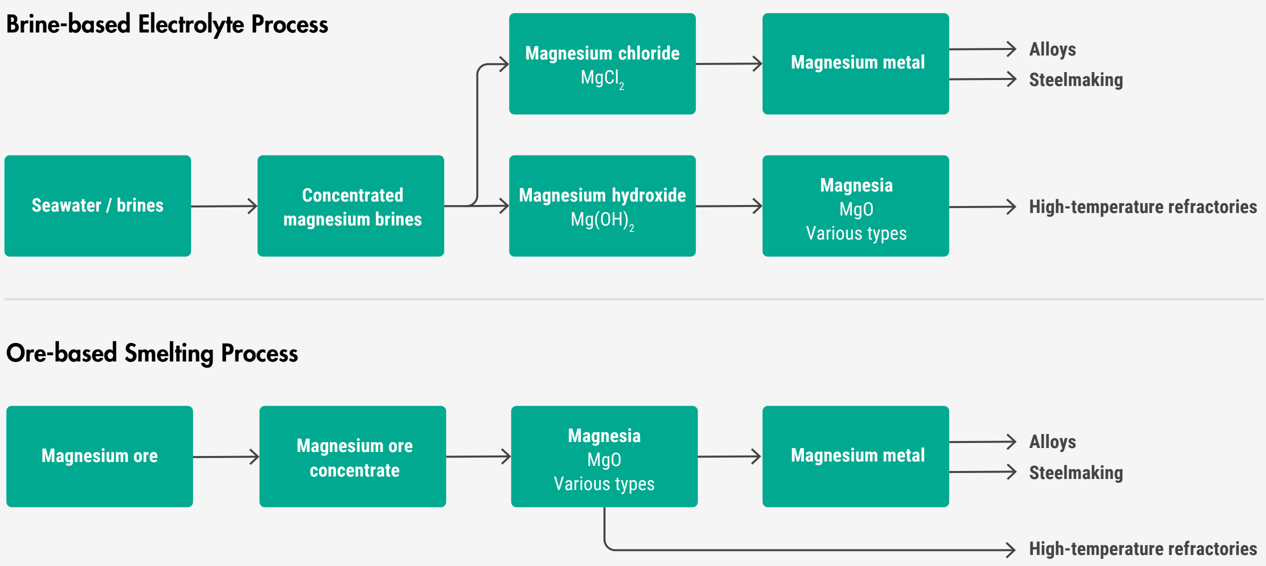


Table 11: Relevant magnesium supply chain commodities, with their characteristics and suitability for stockpiling. Green shaded rows indicate this supply chain's recommended stockpile commodities.

Product	Feasible for stockpiling?	Advantages	Disadvantages	Additional Information
Concentrated magnesium brine	No		• Large storage volume • Not widely traded	
Magnesium ore concentrate	No		• Large storage space • Production of metal from ores is labor and energy-intensive	• U.S. conducts limited domestic Mg ore mining
Magnesium chloride, $MgCl_2$	Yes	• Some direct applications in non-strategic industries	• Reacts strongly with water	• Store in inert atmosphere • Absorbs water vapor from air
Magnesium hydroxide, $Mg(OH)_2$	Yes	• Precursor for all types of magnesia	• Feedstock material only with no direct uses • Does not serve magnesium metal applications	
Magnesium metal	Yes	• Stockpiling lowers risk from historically overconcentrated and volatile market		• U.S. operates limited metal production capacity
Caustic-calcined magnesia (CCM), MgO	Yes	• Direct applications in non-strategic industries	• Predominantly used in various non-critical industry applications	
Dead-burned magnesia (DBM), MgO	Yes	• High temperature refractories (e.g., for concrete production)		
Fused magnesia (FM), MgO	Yes	• Ultra-high temperature refractories (e.g., for steelmaking)		

As a light metal, magnesium is widely used as an aluminum alloying agent and in multiple critical metallurgical applications. Magnesium-aluminum alloys are lightweight and boast high strength and corrosion resistance with useful applications in the construction, defense, aerospace, and automotive industries. The metallurgical industry uses magnesium alloys to make die casting molds, and steelmakers use magnesium to remove sulfur impurities during the production process of high-strength structural steels.[130] Magnesium is also the key reagent in the dominant Kroll process for producing titanium.[131] Finally, magnesia products are important for the function of high-temperature kilns and furnaces used in heavy industries like concrete and steel. Magnesia (MgO) comes in three forms: caustic-calcined magnesia (CCM), dead burned magnesia (DBM), and fused magnesia (FM). The type of magnesia produced from magnesium hydroxide depends on the temperature used to calcine the hydroxide: CCM is produced at 700~1000 °C, DBM at 1500~2000 °C, and FM at over 2750 °C.

As the eighth most abundant element in the Earth's crust and the third most abundant element in seawater, magnesium exists on Earth in practically inexhaustible[132] supply. Globally, producers employ two main techniques to produce magnesium: extraction from seawater and saline brines and extraction from ores. The U.S. operates one magnesium mine[133] but mainly performs brine extraction, while many other nations, including China, primarily process ores. Magnesium smelting from ores in China via the Pidgeon Process is highly labor- and energy-intensive,[134] making that technique likely to remain economically uncompetitive in the U.S.

Magnesium alloys have gained popularity as a potential alternative to aluminum alloys—the primary material for an extensive variety of products from aircrafts and ships to smartphones and cans. Magnesium alloys are lighter than their aluminum counterparts, making them attractive for applications that value weight minimization (e.g., aerospace and automotive uses). An important exception is that magnesium's conductive and thermal properties do not make magnesium suitable as a substitute for aluminum and copper in electrical wire and cables, such as high-voltage transmission lines (which are primarily aluminum) or electromagnetic generator windings (which are primarily copper).

Among magnesia products, DBM and FM both possess superb temperature resistance and structural integrity, making them optimal as the construction material for industrial heating facilities such as kilns and furnaces. DBM is used for high temperature but more standard industrial processes, while FM's high purity and dense crystalline structure allow it to withstand the harsh conditions of the most intensive of industrial processes. For example, one would likely see DBM used in concrete manufacturing plants that reach ~1300 °C. FM's higher temperature resistance makes it optimal for use in steelmaking, which can reach temperatures of 1600~3200 °C. CCM is a more reactive version of magnesia with a variety of applications including removal of sulfur from flue gas, removal of heavy metals from water, livestock feeds, and fertilizers.

Future energy and transportation usage of magnesium in aluminum-based alloys may reach 10-20 thousand tons per year[135] in coming decades relative to current total U.S. consumption of around 50 thousand tons per year—with future magnesium consumption potentially ballooning exponentially if direct substitution of magnesium for aluminum in vehicles, construction, and consumer products accelerates. In the face of magnesium's increasing value, the metal's history of supply volatility highlights its importance within U.S. critical minerals strategy. Only one primary magnesium metal smelter exists in the U.S.; in late 2021, U.S. Magnesium halted magnesium production[136] following major equipment failures, while continuing to produce lithium from brine. In fall 2024, U.S. Magnesium idled its Utah plant[137] entirely in response to low lithium prices.

With the limited magnesium ore mining and processing capacity in the U.S., stockpiling efforts prioritizing magnesium should likely seek to accumulate magnesium metal and magnesium hydroxide. Magnesium hydroxide is substantially more stable than other magnesium compounds and allows for production of any of the three types of magnesia. Magnesium metal is directly used in industry, sits downstream of brine-based magnesium production, and offers far more stable storage and more advantageous supply chain positioning than its precursor, magnesium chloride.

Lessons Learned for Magnesium

Objectives: In theory, magnesium stockpiling would seek to cover national needs for defense technologies, titanium production, and other key metallurgical processes during a national emergency, while supporting domestic magnesium producers.

Assessment: In practice, narrow stockpiling efforts based on current patterns of magnesium usage may fail to account for and capture national advantages from broader shifts toward magnesium as a more lightweight substitute for aluminum in aerospace, vehicular, structural, and general applications. A prescient U.S. critical minerals strategy might arguably prioritize expanding magnesium production domestically and in partner countries. Given the high energy requirement of producing magnesium metal from magnesium hardrock ores, such efforts should focus primarily on magnesium production from brines.

Manganese (Mn)

Recommended Stockpile Priorities:
Ferromanganese, silicomanganese, manganese sulfate

Summary:

- The predominant use of manganese is for steelmaking, but it is also of growing importance for batteries. An idealized stockpile of manganese would serve both industries and should likely target **ferromanganese, silicomanganese, and manganese sulfate**.
- Ferromanganese and silicomanganese alloys are used directly to make steel, with no viable substitutes existing for either alloy—a vulnerability that has already prompted the national defense stockpile to accumulate considerable stores of both commodities.
- Manganese consumption for batteries is currently quite small relative to steelmaking demand, but high anticipated market growth and near-complete Chinese control over manganese sulfate production highlight manganese sulfate as an increasingly relevant potential stockpiling target.
- Developing domestic battery-grade manganese sulfate capacity and efforts to support more diversified sourcing of manganese ore, ferromanganese, and silicomanganese are promising avenues for increasing manganese supply security.

Figure 12: Simplified manganese supply chain with major commodities.

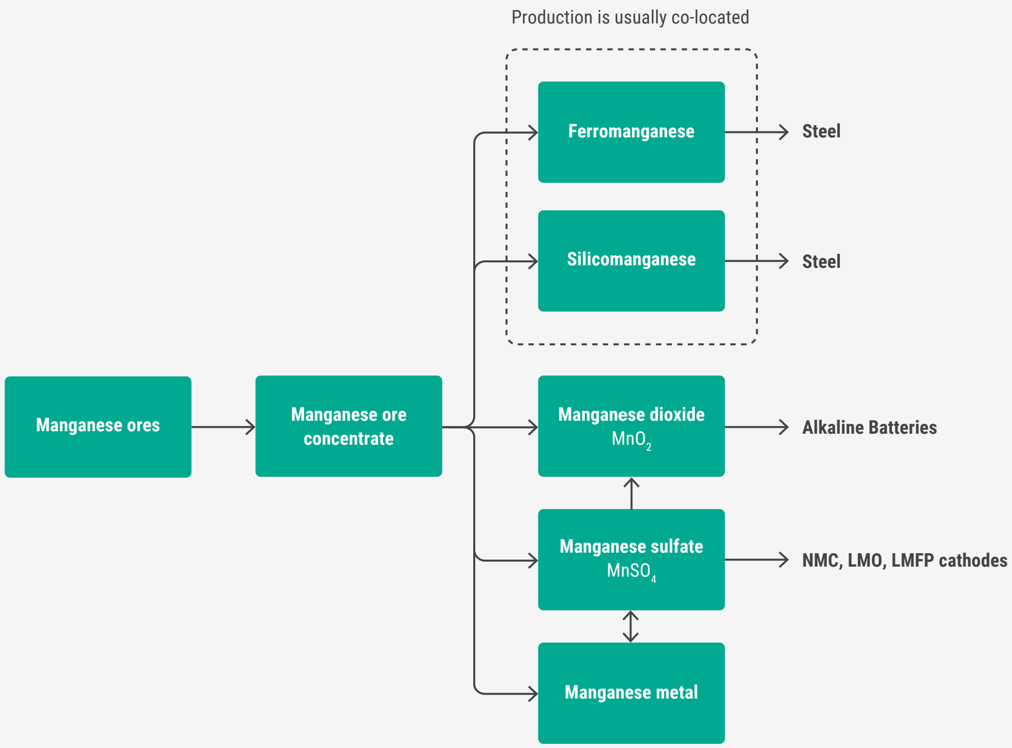


Table 12: Relevant manganese supply chain commodities, with their characteristics and suitability for stockpiling. Green shaded rows indicate this supply chain's recommended stockpile commodities.

Product	Feasible for stockpiling?	Advantages	Disadvantages	Additional Information
Manganese ore concentrate	Yes		• Large storage space	• Pyrolusite and rhodochrosite, for example • Metallurgical purposes require an average grade of ~44% Mn • The U.S. does not mine manganese ore and has only sub-economic reserves
Ferromanganese	Yes	• Direct precursor for steel		• Must sort ferromanganese by carbon content • Essential steelmaking input with no substitutes
Silicomanganese	Yes	• Direct precursor for steel		• Must sort silicomanganese by grade • Essential steelmaking input with no substitutes
Manganese sulfate, $MnSO_4$	Yes	• Market expected to grow quickly	• Only serves battery industry	• All current operating manganese sulfate production capacity is in China
Manganese metal	Yes	• Potential precursor for FeMn, SiMn, and $MnSO_4$	• Few direct applications • Expensive to produce	

Manganese is an indispensable element for the steel industry. During steel production, manganese reacts with and removes oxygen and sulfur impurities that weaken the product. Steel containing manganese also exhibits improved tensile strength, hardness, and formability. No other materials can economically replicate these unique benefits, driving high demand for manganese by steel manufacturers. Accordingly, metallurgical applications consume over 90%[138] of manganese globally, and the mining of manganese ore closely follows steel demand.

The quantity of manganese used by the steel industry greatly exceeds that used in batteries. But the increasing popularity of manganese-containing cathodes, namely NMC, is expected to significantly increase the share of manganese used for energy storage. Lithium manganese iron phosphate (LMFP) batteries are also increasingly entering the commercial battery market. IEA modeling[139] forecasts global manganese demand from energy technologies to increase as much as 5x by 2030 and 17x by 2050—bringing the energy sector from just 1% of the manganese market today to 15% in 2050. Recent Breakthrough Institute modeling suggests that future U.S. energy and transportation sector usage of manganese in steel alloys and batteries could consume between 300 and 500 thousand metric tons[140] of manganese annually, relative to current national consumption of around 680 thousand tons per year.[141] Such growth projections raise particular concern, as China produces an astonishing 97%[142] of the world's battery-grade manganese sulfate. The manganese mining industry's reliance on steel to drive market demand and China's dominant control over manganese sulfate production underscore the value of manganese market support to hedge against price fluctuation, geopolitical risk, and supply chain disruptions.

The salient manganese commodities for steelmaking are ferromanganese (FeMn) and silicomanganese (SiMn)—the former containing more iron, the latter containing more silicon. Both alloys are made up of differing proportions of manganese, iron, silicon, carbon, and other trace elements. The ratio of the four main elements in steel determines its strength, hardness, formability, and resistance to corrosion, abrasion, and various stresses. Based on the desired properties, steelmakers add specific amounts of ferromanganese or silicomanganese to manipulate the steel's chemical composition.

To ensure precision in manufacturing, the steel industry uses a standardized classification system for both ferro- and silicomanganese. Ferromanganese is divided into high, medium, and low carbon alloys based on the quantities of manganese and carbon. Silicomanganese is classified into two grades by its silicon and manganese content: 6517 (65% Mn, 17% Si) and 6014 (60% Mn, 14% Si).

Relatively few processing stages are required to obtain manganese alloys from manganese ores, most commonly pyrolusite (MnO_2). First, manganese ores undergo physical processing (e.g., crushing and screening) and are mixed with a reducing agent (e.g., coal) to reduce MnO_2 into elemental manganese. This mixture is heated to 1200~1600 °C to facilitate this reaction. Smelters then add iron to the molten manganese to make ferromanganese. Often, a sizable amount of MnO_2 goes unreduced and remains in the residual slag from ferromanganese production. Most facilities recycle this slag to make silicomanganese, so ferromanganese and silicomanganese productions are typically co-located. Annual domestic consumption of ferromanganese has remained ~100,000 tons greater than that of silicomanganese (FeMn: ~330,000 tons/year. SiMn: ~230,000 tons/year[143]). The United States currently hosts some manganese smelting capacity (around 150,000 tons annually) that produces ferromanganese and silicomanganese. This capacity raises some possibility of manganese ore concentrate stockpiling, but most U.S. geologic manganese deposits are too low-grade to be economical, while ore concentrates would depend on—and could be bottlenecked by—smelting capacity for conversion into forms usable in steelmaking.

Manganese sulfate requires leaching manganese ore concentrate in sulfuric acid, yielding low-purity manganese sulfate. Subsequent purification is needed to produce battery-grade manganese sulfate. An alternative production route involves the production of manganese metal from ore concentrates, then the production of manganese sulfate from manganese metal. Most Chinese manufacturers follow the concentrate-sulfate technique, but the concentrate-metal-sulfate technique may become more relevant as entrepreneurs attempt to develop Western manganese sulfate production capacity. While China holds a near monopoly of the manganese sulfate industry, it imports a large portion of its manganese ore concentrates. South Africa, Gabon, and Australia (in decreasing order of production) together supply about 75%[144] of the world's manganese.

Ferromanganese and silicomanganese are both stable metal alloys, and both theoretically offer attractive options for long-term storage. A stockpile should sort ferromanganese by carbon content and separate silicomanganese into 6517 or 6014 to effectively integrate with the steel industry's categorization system. Meanwhile, a stockpile of manganese sulfate would directly protect the battery sector from supply chain disruption, particularly given that the U.S. has no manganese sulfate production capacity.

The NDS[145] currently stores manganese ore and high carbon ferromanganese. As of 2022,[146] the NDS held 291,000 metric tons of manganese ore and 104,000 metric tons of ferromanganese. The NDS is approved to stockpile manganese metal but does not do so at present according to public reports.

Manganese constitutes approximately 31% of the mass of seafloor polymetallic nodules, making up a similar[147] share[148] of around 30% of the economic value of nodule resources. The high mass fraction of manganese in nodules makes polymetallic nodules somewhat suitable for stockpiling manganese, with corresponding benefits for nickel and cobalt markets as described elsewhere in this report. Processing of polymetallic nodules can yield manganese silicate usable in the steel sector or manganese sulfate[149] usable for battery applications, manganese oxide, or a manganese carbonate product.

Lessons Learned for Manganese

Objectives: The conceivable goal of U.S. manganese stockpiling would be to keep essential portions of the domestic steel and battery sectors operating during a crisis and to support the limited capacity of the U.S. manganese smelting and mining industry.

Assessment: The NDS currently contains over 100,000 tons of stockpiled ferromanganese and close to 300,000 tons of manganese ore,[150] perhaps sufficient for one year of current economy-wide usage. The U.S. has limited overall manganese mining potential and minimal manganese sulfate production for batteries. Developing domestic battery-grade manganese sulfate capacity and efforts to support more diversified sourcing of manganese ore, ferromanganese, and silicomanganese are promising avenues for increasing manganese supply security.

Nickel (Ni)

Recommended Stockpile Priorities:
Nickel sulfate, nickel metal, ferronickel

Summary:

- Given major bottlenecks in nickel smelting and manufacturing of nickel-based battery compounds, a short-term stockpiling strategy targeting nickel should focus on **nickel sulfate**, **nickel metal**, and **ferronickel**, working around the limitations of current U.S. nickel supply chain capabilities and serving the various domestic industries that rely on nickel products.
- A long-term nickel stockpiling strategy could also consider storing **mixed nickel-cobalt hydroxide precipitate (MHP)** and **mixed nickel-cobalt sulfide precipitate (MSP)**, contingent upon diversification of downstream MHP/MSP processing capacity beyond China and Indonesia.
- New nickel processing techniques have driven profound market shifts over the last decade. Any nickel stockpiling strategy should closely monitor market dynamics and respond proactively to continuing changes in nickel supply chains.
- Efforts to facilitate and support domestic nickel mine, smelter, and battery chemical projects may offer a greater return on investment for U.S. nickel supply security, although the market role of a mineral reserve program could aid in advancing such projects.

Figure 13: Simplified nickel supply chains with major commodities.

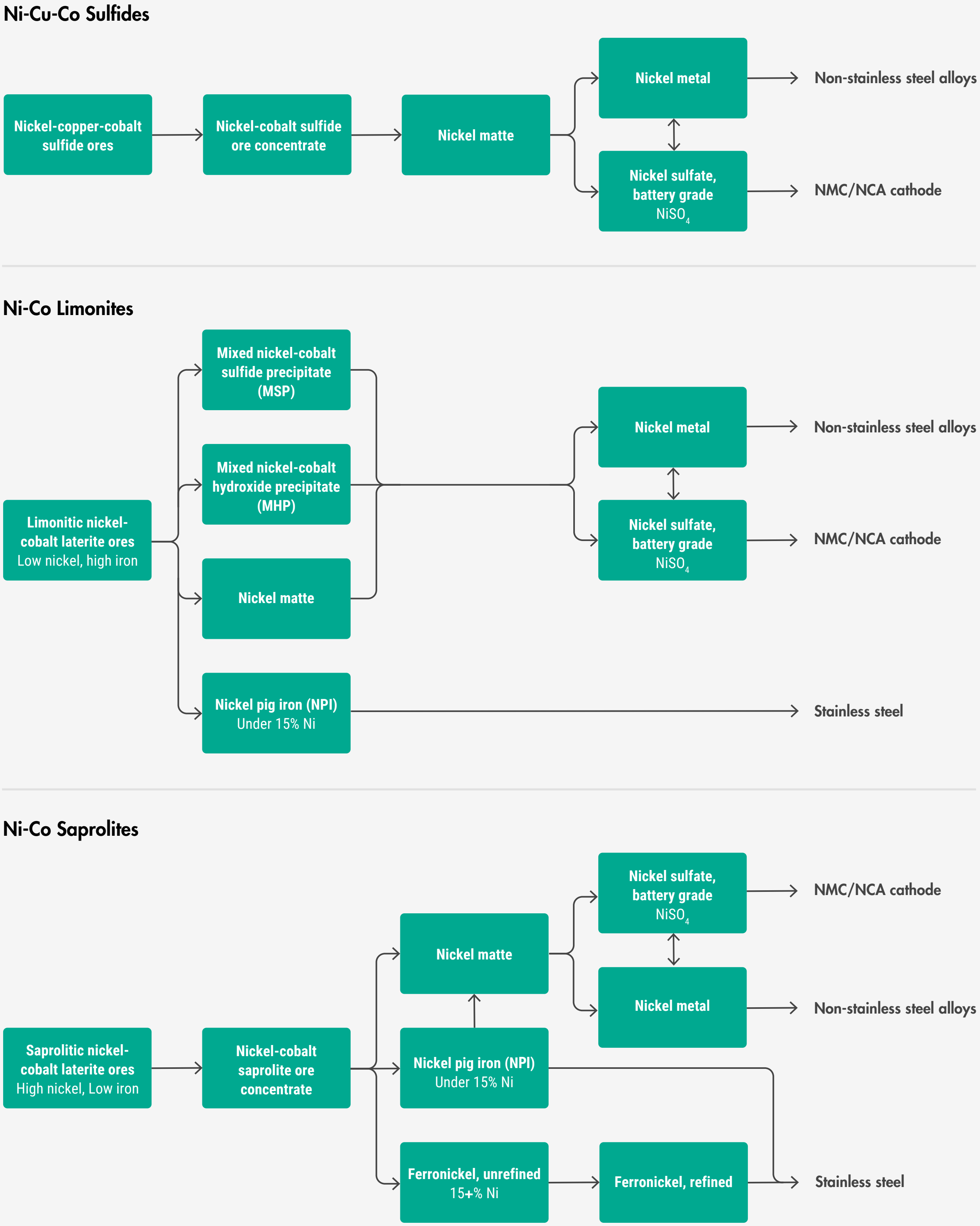


Table 13: Relevant nickel supply chain commodities, with their characteristics and suitability for stockpiling. Green shaded rows indicate this supply chain's recommended stockpile commodities.

Product	Feasible for stockpiling?	Advantages	Disadvantages	Additional Information
Nickel saprolite ore concentrate	No		• Large storage space	• The U.S. does not mine any nickel saprolite ore
Nickel sulfide ore concentrate	No		• Large storage space	• The U.S. mines nickel sulfide ore, but exports ore concentrates for processing
Nickel matte	Yes	• Precursor for Ni metal and Ni sulfate	• Feedstock material only with no direct uses • Does not serve stainless steel applications	
Nickel pig iron	Yes	• Precursor for Ni metal, Ni sulfate, and stainless steel	• Feedstock material only with no direct uses	• Incompatible with U.S. stainless steel facilities
Ferronickel	Yes	• Direct precursor for stainless steel	• Feedstock material only with no direct uses	
Mixed nickel-cobalt hydroxide precipitate (MHP)	Yes	• Precursor for Ni metal and Ni sulfate	• Feedstock material only with no direct uses • Does not serve stainless steel applications	
Mixed nickel-cobalt sulfide precipitate (MSP)	Yes	• Precursor for Ni metal and Ni sulfate	• Feedstock material only with no direct uses • Does not serve stainless steel applications	
Nickel metal	Yes	• Applications in non-stainless steel alloys • Can supply Ni sulfate based on market demands	• Does not serve stainless steel applications	
Nickel sulfate, $NiSO_4$	Yes	• Direct precursor for batteries • Can serve Ni metal based on market demands	• Does not serve stainless steel applications • Flammable	

Nickel's importance as a critical mineral stems from its roles in stainless steel, battery electrodes, and alloys. Demand for nickel is expected to double globally by 2040[151] as nickel-containing battery cathode material usage by EV manufacturers increases and as large infrastructure projects consume stainless steel and nickel alloys. Future U.S. energy and automotive sector nickel usage alone could reach 360 to 570 thousand metric tons per year,[152] equivalent to 200-300% of current national consumption.

Nickel ores are divided into two categories: laterites (exhibiting high iron content) and sulfides. Nickel-rich laterites are known as high-grade saprolites; those with lower nickel content are low-grade limonites. Each of these nickel ores requires unique processing that best aligns with their specific geochemistry. These processing considerations have produced three distinct global nickel supply chains—a framework that introduces complicated market dynamics based on the geographical origin(s) of different sources of nickel.

Historically, refineries have relied mostly on saprolites to produce an iron-nickel alloy known as ferronickel for direct use in making stainless steel. With lower iron contents, limonites and sulfides cannot produce ferronickel but are well suited to make nickel metal (used in non-stainless steel alloys) and nickel sulfate (used in batteries). Another classification system accounts for this division in the nickel market by labeling high-purity nickel products (e.g., battery-grade nickel sulfate and nickel metal) as Class I nickel and lower purity products (e.g., ferronickel) as Class II nickel.

Nickel supply chain considerations are further complicated by recent Chinese technological advancements and supply chain strategies. Aiming to escape the Western-dominated nickel industry of the early 2000s, Chinese companies innovated a method to use nickel pig iron—a lower-grade substitute for ferronickel—to produce stainless steel at far lower cost than foreign competitors, albeit with a higher environmental pollution burden. At the same time, China invested heavily in Indonesia's mining sector to access extensive but untapped Indonesian laterite deposits. With a secure nickel source and the ability to cheaply manufacture stainless steel using nickel pig iron, China's share of the stainless steel industry skyrocketed from ~5% in 2000 to ~55% in 2021,[153] while Indonesia's nickel mine production climbed from 358,000 tons in 2017 to 2.2 million tons in 2022.[154]

Today, the nickel industry remains in a state of upheaval thanks to these new Chinese processes capable of converting Indonesia's low-grade laterite deposits into Class I nickel products. Since implementing this technology in 2022, Chinese refineries operating out of Indonesia have flooded the market with cheap nickel. Sudden oversupply cut global nickel prices by over 60%[155] and shocked[156] even the world's largest mining companies[157] into suspending operations en masse.[158]

Given that only Chinese refineries can currently process Indonesian nickel intermediates (e.g., mixed hydroxide/sulfide precipitate, nickel pig iron, laterite-sourced nickel matte), we eliminate consideration of these intermediates for any short-term recommendations regarding a nickel stockpiling strategy. A long-term nickel supply strategy could aim to adopt relevant downstream refining techniques and begin sourcing nickel from Indonesia, but environmental and labor issues in Indonesia's mining sector raise considerable environmental, social, and governance concerns.[159]

Seafloor polymetallic nodules could offer an alternative long-term strategy to supply a strategic nickel stockpile. Such nodules contain valuable quantities of nickel in addition to manganese, cobalt, and copper, with nickel likely most heavily influencing the economics of any future seafloor nodule harvesting in the Clarion Clipperton Zone, the largest known seafloor nodule field (nickel may represent 35%[160] to 45%[161] of the post-processing gross value of collected nodules). Assuming a 95% recovery rate, a fleet of 10 production ships that each collects 3 million metric tons[162] of dry nodules per year would produce 370,000 tons of nickel annually—enough to potentially single-handedly meet lower end projections of future U.S. energy and transportation sector nickel demand.

Globally, commercial-scale nodule collection has not yet begun, and pathways for processing polymetallic nodules have yet to be definitely established. Some companies are exploring the adaptation of pyrometallurgical techniques[163] used to process saprolites to yield a nickel-cobalt-copper matte[164] from which downstream steps can produce battery-grade nickel sulfate. Other pathways[165] may chemically leach nodules to produce MSP or sheets of nickel cathode metal.

Overall, the most notable challenge of developing a nickel stockpile revolves around the three, separate supply chains that result from incompatible nickel ore chemistries. Current limitations in the present-day U.S. supply chain eliminate many of these complexities from consideration due to a lack of relevant operating downstream refining or upstream mining capacity. However, further evolutions of the global nickel market may eventually necessitate re-evaluating the stockpiling utility of nickel commodities derived from laterite ores.

As such, we identify ferronickel, nickel metal, and nickel sulfate as the most strategically advantageous short-term choices for any stockpiling efforts prioritizing nickel. Ferronickel would support the stainless steel industry given its chemical stability and its necessity for the production of stainless steel. Nickel sulfate and nickel metal both exhibit favorable stockpiling characteristics and can support battery nickel applications. Both are chemically stable and have, in practice, been used as feedstock to produce the other commodity[166] in response to shifting demand.

Lessons Learned for Nickel

Objectives: Similar to manganese, nickel stockpiling would likely aim to insulate the domestic steel and battery sectors from supply disruptions and ensure offtake for domestic nickel mine projects.

Assessment: The global nickel market currently confronts low prices amid continued expansion of nickel mining and smelting capacity in Indonesia,[167] favoring near-term accumulation of a physical nickel reserve. The U.S. has high domestic nickel mining potential but confronts major downstream bottlenecks in nickel smelting and manufacturing nickel-based battery compounds. Efforts to facilitate and support domestic nickel mine, smelter, and battery chemical projects may offer a greater return on investment for U.S. nickel supply security, although the market role of a mineral reserve program could aid in advancing such a strategy.

Rare earth elements (REEs):

Neodymium-Praseodymium Alloy (NdPr), Terbium (Tb), Dysprosium (Dy)

Recommended Stockpile Priorities:

Hard rock ore concentrate, terbium oxide, dysprosium oxide, neodymium-praseodymium oxide

Summary:

- In the short term, a stockpiling program prioritizing rare earth elements should accumulate **hard rock rare earth ore concentrates** to support domestic and allied rare earth mine projects, potentially reduce exports of mined ores, and amass feedstock material to hedge against crisis events.
- Over the long term (assuming higher domestic rare earth ore processing capacity) stockpiling efforts should shift to target **rare earths in oxide form (terbium oxide, dysprosium oxide, and neodymium-praseodymium oxide)** to provide a direct feedstock to magnet manufacturers.
- Limited domestic and allied capacity in both the rare earth ore processing sector and the rare earth permanent magnet manufacturing sector greatly complicates any near-term U.S. rare earth stockpiling strategy.
- Meaningful rare earth permanent magnet supply security directly depends on continued development of rare earth mining, processing, and magnet manufacturing capacity, both domestically and in partner countries.

Figure 14: Simplified rare earth element supply chain with major commodities.

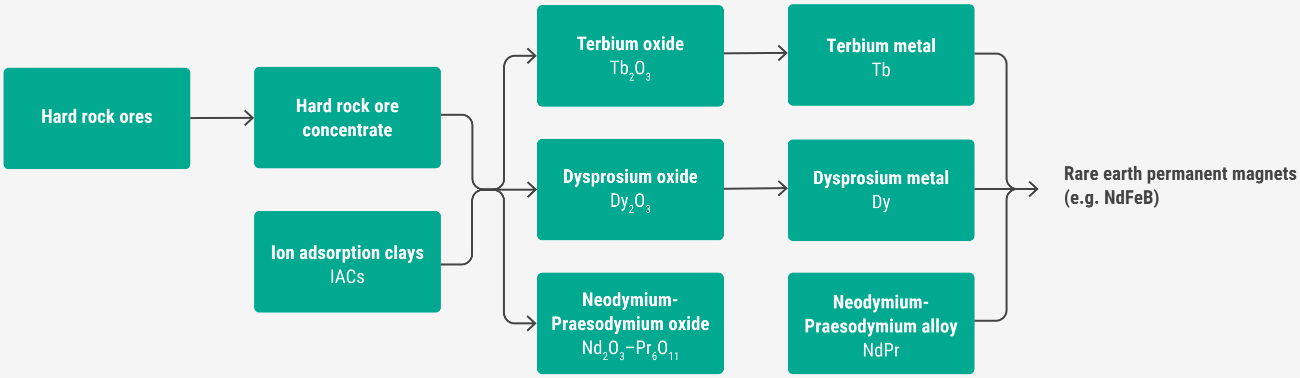


Table 14: Relevant rare earth supply chain commodities, with their characteristics and suitability for stockpiling. Green shaded rows indicate this supply chain's recommended stockpile commodities.

Product	Feasible for stockpiling?	Advantages	Disadvantages	Additional Information
Ion adsorption clays (IACs)	No	• Higher terbium and dysprosium content	• Not widely traded	• Production mainly limited to China and often processed on site
Hard rock ore concentrate	Yes	• Stable	• Requires rare earth ore processing to separate rare earth commodities	• Carbonatite deposits like Mountain Pass, CA, for example
NdPr oxide, 75% Nd_2O_3 + 25% Pr_6O_{11}	Yes	• Stable • Primary feedstock for rare earth permanent magnet manufacturers	• Requires extensive further processing to produce magnet powder and magnets	• Limited processing capacity outside of China • The U.S. currently operates minimal ore processing facilities, though projects currently under development could soon expand processing capacities
Terbium oxide, Tb_2O_3	Yes	• Stable • Primary feedstock for rare earth permanent magnet manufacturers	• Requires extensive further processing to produce magnet powder and magnets	
Dysprosium oxide, Dy_2O_3	Yes	• Stable • Primary feedstock for rare earth permanent magnet manufacturers	• Requires extensive further processing to produce magnet powder and magnets	
NdPr metal alloy	No	• Downstream: direct input for magnet production	• Requires storage in inert gas or oil • Often produced on-site and processed directly into magnet powder without leaving facility	
Terbium metal	No	• Downstream: direct input for magnet production	• Requires storage in inert gas or oil • Often produced on-site and processed directly into magnet powder without leaving facility	
Dysprosium metal	No	• Downstream: direct input for magnet production	• Requires storage in inert gas or oil • Often produced on-site and processed directly into magnet powder without leaving facility	

Rare earth elements (REEs) refer to a group of 17 individual elements. Of these, neodymium, praseodymium, terbium, and dysprosium occupy particular importance given their use in permanent magnets[168] for motors in electric vehicles, wind turbines, and defense technologies. Over the coming decades, domestic energy and transportation applications for rare earths alone may require 7,600 to 12,800 tons[169] of neodymium, praseodymium, terbium, and dysprosium annually, likely exceeding current U.S. production by 50-100%. Freeing U.S. REE supply chains from dependence on Chinese producers will prove crucial for national energy and defense priorities, given staggering U.S. import reliance[170] and China's history of weaponizing rare earth exports.[171]

The REE supply chain stems from two dominant sources of raw materials: hard rock deposits such as the carbonatites mined at the Mountain Pass facility in California, and shallow clay beds known as ionic adsorption clays (IACs) mainly developed in China. Hard rock mines mill excavated ores into an ore concentrate that contains an assemblage of REEs. Separation facilities then leach the ore concentrate and sequentially precipitate individual REEs in the form of rare earth oxides. Production from IAC deposits requires the same processing except that the clay materials often do not require milling and instead can immediately undergo leaching at the mine site. Refining facilities convert[172] the oxides to their metal forms, which manufacturers ultimately incorporate[173] into materials like the neodymium-iron-boron (NdFeB) alloys contained in rare earth permanent magnets.

Importantly, rare earth alloy production typically occurs in close spatial proximity with rare earth magnet manufacturing. Rare earth materials like NdFeB alloys require further specialized processing and milling to produce fine particles referred to as magnet powder potentially as small as two to three microns[174] in diameter. Magnet powder carries a risk of ignition[175] upon exposure to air, imposing substantial difficulties on storage or shipment of such material. Thus, manufacturers often directly incorporate powder into magnets on-site through shaping and pressing under a magnetic field. The blocks undergo densification in a sintering furnace[176] followed by coating to prevent corrosion, at which point manufacturers cut, shape, and magnetize the blocks to produce permanent magnets suitable for end users.

Hard rock ore concentrates and oxide forms of neodymium, praseodymium, terbium, and dysprosium do not pose any particular storage difficulties. Meanwhile, stockpiling NdPr alloys, terbium metal, and dysprosium metal requires storage under inert gases or oils to accommodate their particular reactivity to air and moisture. In theory, stockpiling IAC materials would offer an advantage as they carry higher concentrations[177] of terbium, dysprosium, and other heavy REEs than hard rock ores. In practice, however, IAC operations often process materials on-site directly into rare earth oxides. China's dominance[178] in IAC production further limits the viability of stockpiling IAC materials given their history of limiting exports[179] of upstream materials in favor of exporting value-added downstream rare earth products. In addition to producing most of the REEs sourced from IAC deposits globally, China also accounted for 50-65% of global hard rock REE mine production in the 2021-2023 period, according to our calculations.

Any stockpiling program prioritizing rare earths must grapple with China's 90% share[180] of global rare earth processing capacity and permanent magnet manufacturing capacity,[181] considerations that dramatically complicate selection of which forms of neodymium, praseodymium, terbium, and dysprosium to stockpile. In particular, China effectively holds a monopoly[182] on processing terbium, dysprosium, and other heavy REEs and has politically blocked export of rare earth extraction and separation technology[183] to protect its technical advantages. Friendly supply chains have only recently begun[184] to develop[185] their own processing capacities, led by the Mountain[186] Pass[187] mine in California, which historically exported[188] all its ore concentrates to China but is gradually expanding capacity to process ores into separated rare earth oxides.

In the case of rare earths, such considerations emphasize the conclusion that stockpiling efforts alone cannot solve U.S. rare earth supply security challenges, which demand a more extensive policy strategy to develop new processing and magnet manufacturing facilities. Such efforts will benefit from policy support to protect alternative supply chains from market manipulation or price volatility that might otherwise force projects to cease operations.

Stockpiling efforts would not prove effective without developing added downstream processing capacity. In the short term, a stockpiling program might seek to accumulate hard rock rare earth ore concentrates to ensure offtake for domestic and allied rare earth mine projects and create an emergency reserve of feedstock in the event of global supply disruptions. Stockpiling of ore concentrates can also support rare earth element commodity chains beyond Nd, Dy, Pr, and Tb, such as lanthanum, samarium, and gadolinium. Over the longer term, stockpiling efforts could shift to stockpiling NdPr, Dy, and Tb rare earth oxides to support new, expanded rare earth ore processing capacity while amassing a more usable direct feedstock for magnet manufacturers.

Lessons Learned for Rare Earth Elements

Objectives: In all likelihood, rare earth element stockpiling would prioritize accommodating defense technology demand for rare earth permanent magnets in the event of a crisis scenario.

Assessment: Acute bottlenecks in domestic capabilities for processing rare earth ore concentrates into separated rare earth oxides and for the manufacture of rare earth permanent magnets pose significant challenges to any U.S. rare earth element stockpiling strategy. Meaningful rare earth permanent magnet supply security depends more directly upon continued development of rare earth mining, processing, and magnet manufacturing capacity, both domestically and in partner countries.

Tellurium (Te)

Recommended Stockpile Priority:
High-grade tellurium metal (99.999+%)

Summary:

- Incomplete domestic tellurium supply chain capacity limits practical stockpiling options to downstream tellurium products. Among these, we recommend **high-grade (99.999+%) tellurium metal** as the core commodity for any stockpile targeting tellurium.
- With limited domestic capacity to produce tellurium dioxide and low-grade tellurium, copper telluride stockpiling would require expansion of American copper refinery capacity and downstream tellurium processing capabilities.
- Overall, a modest effort to develop low-grade tellurium metal production capacity in the U.S. would fill gaps in the U.S. tellurium supply chain and resolve any foreseeable future tellurium supply concerns.

Figure 15: Simplified tellurium supply chain with major commodities.

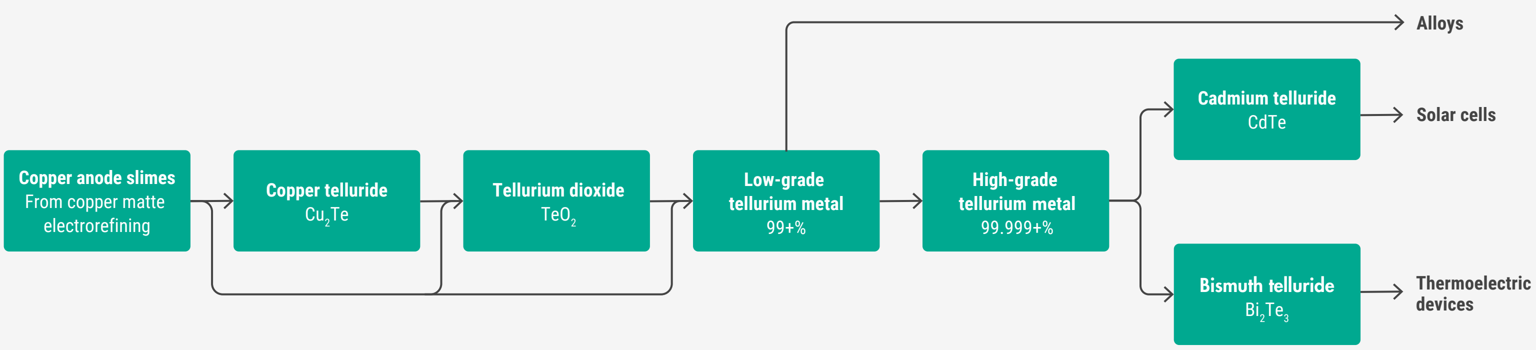


Table 15: Relevant tellurium supply chain commodities, with their characteristics and suitability for stockpiling. Green shaded row indicates this supply chain's recommended stockpile commodity.

Product	Feasible for stockpiling?	Advantages	Disadvantages	Additional Information
Copper anode slimes	Yes	• More efficient use of storage space than copper ores • Stockpile could help avoid disposal of slimes		• U.S. operates limited production
Copper telluride, Cu_2Te	Yes		• Requires further processing to produce usable tellurium compounds	• U.S. operates limited production; must export for further processing • China currently operates most copper telluride processing capacity
Tellurium dioxide, TeO_2	Yes		• Requires further processing to produce usable tellurium compounds	• China currently operates most tellurium metal dioxide processing capacity
Low-grade tellurium metal, 99+%	Yes	• Direct precursor for alloys	• Feedstock material only with no direct uses	• U.S. currently imports most low-grade tellurium metal
High-grade tellurium metal, 99.999+%	Yes	• Serves both CdTe and Bi_2Te_3 demand • Can serve alloy demand	• Feedstock material only with no direct uses • May not be able to serve alloy applications economically	
Cadmium telluride, CdTe	Yes	• Direct precursor for solar cells	• Only serves solar cell demand	
Bismuth telluride, Bi_2Te_3	Yes	• Direct precursor for thermoelectrics	• Only serves thermoelectric demand	

Tellurium is a rare metal required to produce cadmium tellurium (CdTe) solar panels and bismuth telluride, Bi_2Te_3 (BiTe) thermoelectric products—heating/cooling devices that require no liquid and can be made much smaller than traditional temperature control systems. Tellurium metal is also used directly in alloys and some semiconductors. Solar cells make up 40% of tellurium demand, thermoelectric products make up 30%, and alloys make up 15%.[189] U.S. energy system models suggest domestic energy sector usage[190] of at least 170 tons of tellurium per year or more in coming decades. In February 2025, the Chinese government announced tighter restrictions on exports of tellurium to the United States, escalating U.S. tellurium supply chain risks.

Only 500~600 tons[191] of tellurium are produced worldwide annually, with around two-thirds originating in China. The U.S., while not a major producer, is one of the few countries that produce primary tellurium. RioTinto's Kennecott refinery[192] in Utah produces about 20 tons of tellurium as copper telluride per year. The Freeport-McMoRan copper refinery in El Paso, Texas, reportedly also produced tellurium as recently as 2021,[193] while the ASARCO copper refinery in Amarillo, Texas, also historically produced tellurium[194] but has been closed since 2022.[195]

As an extremely scarce element in the Earth's crust, most of the world's tellurium is produced as a byproduct from electrolytic copper refineries. As copper undergoes electrorefining in these facilities, impurities sink to the bottom of the electrolytic cell. The resultant material is referred to as copper anode slime, and it is from this slime that tellurium is extracted. Different copper anode slime processing techniques yield different tellurium chemicals: copper telluride, tellurium dioxide, or low-grade tellurium metal. RioTinto's copper refinery produces copper telluride while the ASARCO facility has reportedly produced tellurium dioxide and low-grade tellurium metal in the past. The U.S. exports copper telluride to be refined abroad and imports low-grade tellurium metal. Domestic facilities purify low-grade tellurium imports (99+%) into high-grade tellurium (99.999+%) that is of suitable quality to make CdTe and BiTe.

The primary challenge in designing a national tellurium stockpile is circumventing the gaps in the U.S. tellurium supply chain. Copper anode slimes and copper telluride are both upstream tellurium-containing materials produced domestically. Stockpiling upstream materials could serve all downstream tellurium applications and incentivize collection of wastes with byproduct recovery potential like copper anode slimes. But contents of an upstream stockpile currently depend on being exported for further processing due to a lack of domestic capabilities, effectively defeating the purpose of a stockpile. Further downstream, low-grade and high-grade tellurium represent more attractive commodities for stockpiling due to their direct usability or convertibility for downstream applications. The U.S. currently imports low-grade tellurium and performs some domestic tellurium purification. A tellurium metal stockpile could mostly supply solar panels and thermoelectrics, though stocks of low-grade tellurium metal can also supply manufacturers of tellurium alloys. BiTe and CdTe are non-versatile, specialized commodities and are therefore not recommended for stockpiling, as stores of these materials are unable to serve other industries.

Lessons Learned for Tellurium

Objectives: U.S. mineral stockpiling efforts likely would not prioritize tellurium but would rather redirect tellurium supplies from the solar energy sector to alloy, imaging, thermoelectric, and any other strategic applications in the event of a national emergency.

Assessment: Tellurium production occurs via byproduct recovery during copper metal refining. The U.S. recovers tellurium-bearing byproducts from copper refineries but exports materials abroad to be processed into low-grade tellurium metal before refining imported low-grade tellurium into high-grade tellurium. Overall, a modest effort to develop low-grade tellurium metal production capacity in the U.S. would fill gaps in the U.S. tellurium supply chain and resolve any foreseeable future tellurium supply concerns.

Zinc (Zn)

Recommended Stockpile Priority:

Zinc metal

Summary:

- A strategic reserve program seeking to stockpile zinc should prioritize stockpiling **zinc metal** as its primary commodity, given its favorable storage characteristics and immediate usability in the galvanizing and alloying industries.
- A U.S. zinc supply security strategy will likely have to prioritize zinc project development both domestically and in partner countries, with a particular emphasis on expanding domestic zinc refining.
- Supplemental stockpiling of zinc ore concentrates and electric arc furnace dust could help support mine projects and retain useful waste products, while ensuring availability of feedstocks for zinc metal production in the event of upstream supply disruptions.
- With investments in byproduct recovery capabilities at domestic and overseas facilities, zinc mining and refining may also support recovery of germanium, gallium, and cadmium, depending on zinc ore composition.

Figure 16: Simplified zinc supply chain with major commodities.

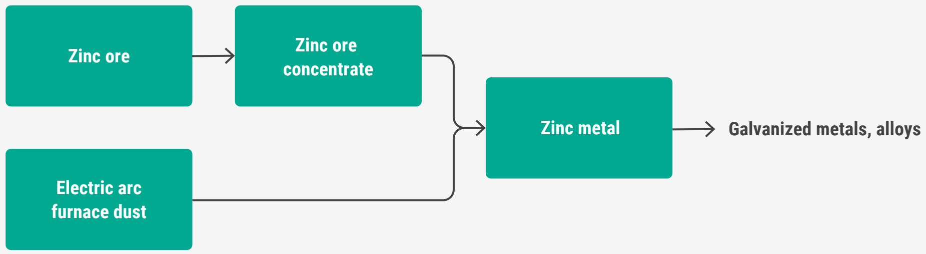


Table 16: Relevant zinc supply chain commodities, with their characteristics and suitability for stockpiling. Green shaded row indicates this supply chain's recommended stockpile commodity.

Product	Feasible for stockpiling?	Advantages	Disadvantages	Additional Information
Zinc ore concentrate	Yes, with precautions	• Widely traded • May contain gallium, germanium, or cadmium	• Large storage space • Requires further processing to produce usable metal • Flammability risk under certain air, temperature, and moisture conditions	• Sphalerite, for example
Electric arc furnace dust	Yes	• Alternative feedstock to zinc ore concentrates	• Requires further processing to produce usable metal • Availability depends on secondary steel market	• Waelz oxide, for example
Zinc metal, Zn	Yes	• Downstream; minimal further processing needed for end uses		

Zinc plays an essential role in modern industry as the main component of coatings that prevent corrosion when applied to steel and other metal products through the galvanization process. Though many industrial and consumer products also contain zinc, galvanization alone accounts for over half of all zinc[196] consumption globally and constitutes the biggest application for zinc in the U.S.[197] As a result, zinc appears in innumerable industrial components including hardware and construction steel, in addition to various alloys such as diecast automotive parts. Future growth[198] in the U.S. power and automobile sectors alone may require 40,000 to 80,000 tons of zinc annually by the late 2030s and 2040s. Meanwhile, the U.S. already relies on imports[199] for roughly three-quarters of its zinc consumption at current rates. This deficit is mainly owing to limited refining capacity; raw mine production could accommodate over 80% of U.S. demand, but most of it must undergo further processing abroad.

Galvanizing applications and zinc-containing alloys require supplies of refined zinc metal. This process begins with mining zinc ores, which mines mill into an ore concentrate after excavation. Smelting facilities then convert the ore concentrates into zinc metal most commonly using hydrometallurgical techniques,[200] as practiced by the only primary zinc smelter[201] in the U.S. This technique involves roasting the ore concentrate and leaching the resulting material in acid, then electrolytically depositing the zinc as metal. Melting the zinc metal allows fabrication of various shaped parts as well as alloys consumed by manufacturing facilities such as galvanizing or diecasting plants. Zinc smelting facilities can also process dust created when producing steel from recycled scrap in electric arc furnaces,[202] yielding new zinc from this alternative feedstock.

Neither electric arc furnace dust nor zinc metal poses any particular storage difficulties, while storage of zinc ore concentrates requires some precautions to minimize risk of fire. Overall, a strategic reserve program targeting zinc should prioritize zinc metal as its primary commodity due to its immediate readiness for industrial applications. Zinc mining[203] is not excessively concentrated in a small number of countries, but stockpiling ore concentrates and electric arc furnace dust would provide secure feedstock availability to maintain zinc metal production in the event of upstream supply chain disruptions. In addition, such supplemental stockpiles would lessen disposal or export of value-bearing arc furnace wastes and support primary zinc mine operations in the U.S.

Lessons Learned for Zinc

Objectives: Presumably, U.S. zinc stockpiling efforts would seek to maintain galvanized steel output and other metallurgical sector needs for national defense during a national emergency while also supporting domestic zinc projects.

Assessment: The U.S. operates limited zinc mining, refining, and recycling capacity but confronts a low ceiling on zinc geologic resources. A U.S. zinc supply security strategy will likely have to prioritize zinc project development both domestically and in partner countries, overall, with a particular emphasis on expanding domestic zinc refining. With investments in byproduct recovery capabilities at domestic and overseas facilities, zinc mining and refining may also support recovery of germanium, gallium, and cadmium, depending on zinc ore composition.

The strategic context of critical mineral stockpiling

Drawing strategic stockpiling lessons from the past and present

The long lead times and high upfront costs of critical mineral projects have traditionally encouraged conservative, risk-averse business strategy within the mineral commodities sector. Even in other, more agile economic sectors, supply chain disruptions can induce shortages—or oversupply—to which markets and producers cannot react quickly enough to alleviate.

With the mining and minerals sector particularly unable to respond rapidly to changing market conditions or geopolitical events, the United States and other nations have historically employed strategic stockpiles to support supply chain continuity in the face of interruptions. Such stockpiles have occasionally served other purposes such as market support, stake acquisition in overseas mineral deposits, and exertion of influence in global mineral markets. Proposed stockpiles often focus on either national security and defense or the avoidance of economic disruptions from supply shocks. However, the trajectory of modern technological developments suggests that the distinction between these two categories is thinning so that the resiliency of a nation's industries and its national security are closely interconnected. Here, we briefly outline and discuss historical and current examples of strategic mineral stockpiling across the world to provide additional insight into the variety of ways that a stockpiling program can be implemented.

China

China's National Food and Strategic Reserves Administration oversees the country's minerals stockpile which was first established in 2006.[204] Extremely little is known about the stockpile's statutory purpose and operation; most available information comes from government announcements released in the program's early years and the major purchases/releases that followed.[205] China has empirically used its stockpile to increase the competitive advantage of Chinese companies but has yet to explicitly announce an intent to use the stockpile to serve its needs during a national emergency. While exact numbers are not available, China has reportedly accumulated 1.5 to 2 million tons of copper, 800,000 to 900,000 tons of aluminum, 250,000 to 400,000 tons of zinc, 7,000 tons of cobalt, and substantial amounts of other commodities including antimony, cadmium, cobalt, gallium, germanium, indium, molybdenum, rare earth elements, tantalum, tin, tungsten, and zirconium.[206, 207] Given the size and maturity of China's stockpile, analyzing its benefits for Chinese companies provides insight into the potential upsides that an American stockpile can yield at a similar stage of development.

Skillful utilization of Chinese mineral stockpiles has made the nation's stockpile program a self-supporting financial vehicle that can influence commodity markets to favor Chinese companies. By filling the stockpile during periods of low prices, China decreases the program's overall costs while also pushing commodity prices upwards to ensure healthy revenues for Chinese suppliers. Amid weak markets in 2008 and 2009, for instance, the Chinese government bought 400,000 metric tons of aluminum, 165,000 metric tons of copper, and 150,000 metric tons of zinc.[208] In this way, the stockpile assists producers (e.g., mines and upstream processors) when it purchases goods.

Executing stockpile releases during periods of high prices benefits downstream industries by driving down the cost of purchasing stockpiled materials. Stockpile disposals under such market conditions earn revenue that can help fund the stockpile program. A stockpile also provides the government with a tool to strategically support companies or industries of interest. This can manifest as prioritizing support for businesses that are most at risk or supporting a broader national policy objective. A notable example of these practices took place in 2021 when China released 100,000 tons of copper, zinc, and aluminum in response to surging commodity prices.[209, 210] The disposal served to assist China's key manufacturing and metallurgical industries.

Chinese provinces have pursued stockpiling of locally produced metals during market downturns, independently of the central government.[211] This model raises interesting potential for state or local governments to participate in stockpiling. A regional stockpiling strategy could more effectively coordinate with industry stakeholders and manage the logistics of siting, releasing, and distributing. These advantages could, however, compromise a stockpile's ability to effectively serve broad national interests or to mobilize in coordination in response to widespread market disruptions.

It is crucial to note that the success of China's stockpile directly derives from the high degree of vertical integration in many Chinese industries. The stockpile can deal exclusively with Chinese companies in both purchases and sales which keeps the stockpile's benefits extremely well contained. A financially oriented stockpile in the United States would operate largely similarly to China's. But an American stockpile will not provide significant strategic advantages without the presence of sizable domestic capacity for adjacent industrial processes.

Japan

The Japanese government established a national stockpiling system for rare metals during the late period of the Cold War, creating a cooperative initiative in 1983 that splits efforts between the public and private sectors.[212] Overseen by Japan Oil, Gas, and Metals National Corporation (JOGMEC), the stated mission of Japan's stockpile is to ensure natural resource security and economic security.[213] Unlike the NDS—which publishes its annual proposed acquisitions and disposals publicly in the *Federal Register*[214]—Japan does not disclose the specific ore types or quantities of its stockpile.[215] This policy aims to avoid influencing the market, as private entities often adjust market strategies in response to stockpile purchases and sales, a dynamic which can exacerbate price fluctuations.[216] The Japanese government aims to maintain 60 days of domestic consumption in its strategic stockpile (42 days' worth in government reserves and 18 days' worth stored in private-sector stockpiles), though they can change that goal to 180 days for minerals with high supply chain risk.[217] The stockpile contains 34 minerals, including cobalt, chromium, gallium, germanium, lithium, manganese, magnesium, nickel, REEs, and silicon.[218]

While Japan's stockpile and minerals policy were enacted in the 1980s, JOGMEC (est. 2004) began investing significantly in supply chain diversification initiatives in the wake of a major diplomatic incident following a Chinese fishing boat collision with two Japanese coastguard vessels in 2010. The detention of the fishing boat's captain by Japanese authorities prompted China to temporarily interrupt rare earth mineral exports to Japan.[219] At the time, Japan's large automobile sector relied on China for almost 90% of its REEs. Since then, JOGMEC developed and implemented a comprehensive plan for supply chain diversification that decreased Japan's REE dependence on China from 90% to around 60% today.[220] Part of JOGMEC's strategy included a reassessment of its stockpile.[221] But much of JOGMEC's successes derive from its other policy efforts: accessible long-term funding for private companies, supporting projects in resource-endowed nations, and international cooperation (e.g., partnerships such as the Minerals Security Partnership, recent talks with Korea on critical minerals policy coordination).[222, 223]

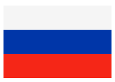
Korea

Korea's national minerals stockpile is operated by the Korean Mine Rehabilitation and Mineral Resources Corporation, a government-related entity that is overseen by Korea's Ministry of Trade, Industry, and Energy (MOTIE). Korea stockpiles 100 days' worth of 33 "critical minerals" to maintain economic security and 10 "strategic critical minerals" that MOTIE deems especially important for Korean industry and rigorously manages. The strategic critical minerals are lithium, nickel, cobalt, manganese, graphite, and 5 REEs (neodymium, dysprosium, terbium, cerium, and lanthanum).[224]

Korea's contemporary stockpiling strategy began in December 2023 with MOTIE's "3050 Strategy." The strategy aims to reduce Korea's import dependence on 185 items—including the aforementioned critical minerals—to 50% by 2030.[225] MOTIE developed the plan via a top-down approach; the ministry identified end-products that are of particular value to Korea's economy and see high supply chain vulnerability. Analysis of the weak points in supply chains for these goods led to the 3050 Strategy's list.

Despite the novelty of the 3050 Strategy, the Korean government is expected to mobilize over 5 trillion won ($3.79 billion) to support its implementation; 200 billion won ($139 million) is reportedly appropriated for lithium alone.[226, 227] Korea recognizes the magnitude of its dependence on China and exposure to global supply chain disruptions. To address these challenges, Korea's government is willing to deploy prodigious investments—the size of which reflects the value Korea places on reducing its vulnerability. Continued implementation of Korea's 3050 Strategy should be carefully observed. Key details may be gleaned that can inform the development of an American strategic stockpile as well as a broader plan for American industrial policy.

Russia



The USSR operated a program of strategic stockpiling as part of its central economic planning and military-industrial strategy. Its aims were to reduce military vulnerability, protect the economy from other major disruptions, and support economic plan fulfillment.[228] In the event of a national emergency, the Soviets designed the stockpile to serve as an accessible reserve for immediate use. Post-Soviet Russia continues to stockpile strategic resources through Gokran (State Precious Metals and Gems Repository) and other agencies.

United States

Past U.S. stockpiling policy emerged in parallel with geopolitical conflict, and the size of the national stockpile vacillated in response to the magnitudes of international tensions. World Wars I and II revealed large-scale supply chain disruptions as being not uncommon occurrences and capable of significant damage spanning many vital American industries. Congress established the NDS in the 1939 Strategic and Critical Minerals Stock Piling Act (hereinafter referred to as the Stockpiling Act). This act and its amendments still direct operations of the NDS today. Stockpiling continued actively through the remainder of the 20th century with notable changes during World War II and at the onset of the Cold War in the early 1960s. The end of the Cold War in 1991 and increased trust in foreign nations as reliable suppliers sparked a downsizing in the NDS, of which Congress determined that 99% was excess to the nation's needs.[229]

While management of the NDS has evolved tremendously since its inception, it is noteworthy that U.S. stockpiling strategy has first and foremost served the interests of national defense. In defining the NDS's statutory purpose, the Stockpiling Act limits the NDS "to serve the interest of national defense only" and prohibits its use "for economic or budgetary purposes."[230] Executive Order 14501 signed by President Biden in October 2021 reiterated that the NDS may only perform releases "when required for use, manufacture, or production for purposes of national defense. No release is authorized for economic or budgetary purposes."[231] There exists, therefore, no precedent for a domestic minerals stockpile whose primary purpose is to mitigate supply chain risk and support industry during peacetime. Enacting such a stockpile—via amendment of the Stockpiling Act or creation of a separate program—would require an act of Congress.

The United States does not lack experience at stockpiling other commodities. The Strategic National Stockpile houses a wide range of medical supplies and has supplied responses to emergencies such as natural disasters, bioterror events, and the COVID-19 pandemic.[232] The Strategic Petroleum Reserve stores oil in underground caverns that can be accessed in response to energy market disruptions.[233] Past national stockpiles have included a helium reserve (discontinued in 2021[234]) and food stockpiles intended to protect farmers from low prices.[235]

Stockpiling insights from supply chain analysis

Modern stockpiling is different from historical stockpiling

Events in recent months and years highlight how a modern mineral stockpiling strategy must respond to a variety of new circumstances that past generations of planners did not need to consider to the same degree. Global industrial supply chains linked by just-in-time trade connections have increased economic sensitivity to trade interruptions, regional conflict, natural disasters, and similar disruptions. Economic coercion often targets individual key minerals or technology sectors. Declines in industrial capabilities domestically and in historically allied countries have, in turn, exposed the United States to greater vulnerabilities. Collectively, many of these contingencies fall well short of a major conflict that might warrant full-scale release of the NDS, let alone the total societal mobilization necessary to rapidly resolve supply chain gaps in a national crisis.

At the same time, the NDS now sits largely depleted relative to its late 20th-century levels of accumulated material reserves. While policymakers might feel a natural compulsion to simply revitalize the NDS to a scale able to meet any and all of the present day's complex needs, a grounded assessment of the NDS's current stockpiles favors a realist's perspective that the United States is starting again nearly from scratch.

In principle, a national critical mineral strategy rightly prioritizing ambitions like U.S. advanced energy and AI technology leadership alongside crisis preparedness must recognize the need for more flexible and proactive management of mineral resources with the ability to respond to diverse scenarios. The statutory rigidity of the NDS suggests a strong need to consider alternative structures for a mineral strategic reserve or similar program, such as a wholly-owned government corporation[236] or a broadened and repurposed Strategic Petroleum Reserve handling critical mineral commodities.[237]

We refer readers to the previous section for a more extensive discussion of historical U.S. strategic mineral stockpiling efforts and similar programs operating in other countries.

Most materials are not difficult to store

From a detailed investigation of these 15 mineral supply chains, we find that most commodities pose few physical stockpiling difficulties in principle. In many cases, private industry has already developed techniques to store and handle even highly reactive materials, and relatively few materials have prohibitive shelf-lives for long-term storage. In general, a stockpiling program could feasibly store most materials for years by adopting common industry precautions.

Technical and logistical considerations do heavily inform stockpile commodity selection within a supply chain, however. The theoretical ability to store several commodities hardly changes the fact that some commodities offer logistical and economic advantages relative to others. In some cases, risk of degradation, physical fragility, or chemical risks do prevent viable or affordable long-term stockpiling of specific commodities, as is the case for lithium hydroxide, germanium wafers, or neodymium-boron rare earth alloy powder, respectively. In other cases, some intermediate materials like lithium sulfate or Bayer liquor typically undergo immediate conversion on-site without leaving the fenceline of a processing facility, disqualifying them from consideration as a stockpiling candidate. Mined ores or minimally processed ore concentrates require large facility volumes to store per unit of finished metal or refined product, imposing logistical disadvantages on stockpiling.

Physical stockpiling may only rarely align with short-term national interests

Near-term efforts to strategically stockpile a mineral would ideally require a favorable coincidence of three factors that are not typically in alignment for the U.S. at present:

1. Adequate downstream industrial capacity to process a stockpiled material and/or to use the material directly in manufactured components or products.
2. Favorable market conditions for acquiring sufficient material at a reasonable price and without exacerbating supply shortages for domestic industry actors.
3. Opportunity to leverage stockpiling efforts to purchase materials from new and existing upstream domestic producers of that commodity, guaranteeing the preservation of strategically valuable supply chain projects.

Stockpiling of a commodity ideally supports preceding supply chain nodes by increasing certainty of purchase for produced materials, but it fundamentally requires domestic industrial capacity at subsequent supply chain nodes to realize the material's full strategic value. Failure to meet the latter condition renders an emergency stockpile strategically useless, while failure to meet the former condition inhibits a stockpile program's ability to function effectively as a market support tool.

At the same time, strategic mineral stockpile accumulation must carefully consider the right timing and execution strategy for building physical mineral reserves. In the past, planners have stressed the importance of keeping U.S. stockpile program actions secret and unpredictable, to avoid detrimental market effects from investment speculation and responding industry actions.[238] At present, several minerals like germanium, gallium, rare earth elements, and copper confront Chinese export bans targeting the U.S. and/or high prices, meaning that stockpile accumulation would only exacerbate price increases and compete detrimentally with industry efforts to source material. Other mineral supply chains like graphite or cobalt remain highly concentrated among Chinese producers, introducing the risk that Chinese policymakers could restrict exports to counteract U.S. stockpiling efforts.

Finally, those managing stockpiling efforts should consider overall U.S. goals for each given mineral supply chain, adapting strategy based on whether or not the U.S. possesses—or is seeking to develop—domestic supply chain capacity. If U.S. chromium supply chain capacity at many steps remains dramatically insufficient with little future hope of establishing competitive capabilities in the sector, stockpiling should be understood as an emergency reserve, considering the strategic applications a commodity chain serves and the volume required to support those industries through a period of supply chain disruption. However, if the U.S. is aiming to become a global player in a commodity market such as lithium, then national strategy should consider the potential of a public sector entity playing a more active market role to support domestic projects and insulate an emerging industry from market volatility.

Together, these factors compel policymakers to think deeply before instinctively pursuing large-scale physical stockpiling of a commodity. In general, supply chain conditions that make near-term physical stockpiling of a given material the right strategic choice for the U.S. are the exception, not the rule.

Ambitious physical stockpiles are a long-term project

If policymakers and military planners determine that the U.S. indeed requires a considerable national mineral stockpile capable of sustaining the country for years through major global upheaval, establishing it will be a prolonged project spanning perhaps a decade or more. Accumulation of materials at scales commensurate with economy-wide consumption will also demand significant expenditures, posing a crucial opportunity cost trade-off relative to alternative policies that seek to develop supply chain capabilities.

Over such a timeframe, program administrators will need to dynamically alter stockpile planning to account for evolving conditions. Changes in end-user technology material use, advances in processing, storage, or recycling capabilities, expanded domestic capacity at key supply chain steps, and shifts in the global industry landscape will demand periodic reevaluation of whether to prioritize new minerals, de-prioritize a commodity, or reorient stockpiling efforts to focus on a different commodity within a mineral supply chain.

Such long-term developments may even include the emergence of entirely new industries. Containing four critical minerals in a single long-term stable resource and offering the potential for new, alternative metal processing pathways, seafloor polymetallic nodules for example may open up new possibilities for national stockpiling strategy by outflanking current constraints in U.S. nickel, manganese, cobalt, and copper mining and processing capacity. Future commercial collection of space-based minerals might similarly challenge existing supply chain paradigms. Far humbler and easier to visualize, continued growth in the circulation of end-of-life equipment and recycled minerals will increasingly challenge linear material flows from extraction to processing to end uses.

The current national defense stockpile isn't the answer

The NDS cannot statutorily serve U.S. industry outside of an armed conflict or national emergency. Similarly, the defense stockpile does not currently have the authority to influence mineral markets through the active buying and selling of materials. The very mission of the NDS "to serve the interest of national defense only" during "times of national emergency"[239] prevents it from acting with the flexibility needed to respond to more varied threats to U.S. critical materials security today. Furthermore, the current NDS posture that gauges stockpile adequacy based on preparedness to supply manufacturers for a year or more during a single crisis event runs counter to more regular cycles of material accumulation and withdrawal. Even with an expanded mission, the NDS in its present state risks falling far short if called upon to meet wider U.S. advanced technology sector needs in the event of major supply chain disruptions. Policymakers arguably should not confine themselves to the structure of the NDS when imagining the institution of a U.S. strategic mineral reserve, its mission, or how it might operate.

Physical stockpiling would not be the primary benefit from a new national mineral reserve

The chief benefit of any new federal mineral reserve program in the near or medium term would involve the reserve's role as a market actor for de-risking domestic mineral and processing projects through market development, insulation from market manipulation by foreign states, and greater flexibility of commodity exchange, rather than from accumulation of physical reserves sufficient to support major industries like the U.S. semiconductor or battery sectors through a prolonged period of crisis. Such a program could situationally oversee physical stockpiling of certain minerals as a market support tool, although financial-only mechanisms may prove amply effective in many cases.

Even if the eventual goal of national stockpiling is to amass a more versatile mineral reserve for prolonged crisis events as an evolution of the current NDS, the lengthy time required to accumulate minerals necessarily forces a stockpile program to weigh its ability to influence mineral markets and benefit domestic producers in the near term. Given such considerations, design of a new national mineral reserve framework may as well consider a more active rather than passive market role.

The U.S. needs to build projects more than it needs to build stockpiles

Most discussions among policy commentators regarding national mineral stockpiling have adopted a high-level perspective on how stockpiling would operate within a future vision for U.S. critical mineral security. But for the U.S.—starting from a position of weakness with only a considerably depleted national defense stockpile to leverage—such aspirational visions are only as achievable as the paths taken to reach them. Those paths are defined mineral by mineral, step by step within mineral supply chains. Starting from the ground up by examining different mineral supply chains in more granular detail thus helps provide new context and a more realistic perspective on the feasibility and value of U.S. mineral stockpiling efforts.

We conclude that potentially prohibitive challenges confront proposals for a grander national stockpile armed with sufficient materials to help key U.S. economic sectors continue operating through a major crisis or supply chain disruptions lasting a year to multiple years. Stockpiling alone is not a substitute for other direct policy support vitally necessary to expand domestic mining or processing capacity long term. A large stockpile of a refined commodity neither automatically solves all supply chain security challenges associated with a critical mineral, nor is necessarily the most impactful intervention of choice for every critical mineral. U.S. geologic resource constraints and supply chain bottlenecks including targeted export bans from China currently pose daunting obstacles to simple physical stockpiling of many minerals. It is difficult to begin saving for a rainy day when storms are already battering the homeland.

To promote long-term U.S. mineral supply security, policymakers must prioritize targeted industrial policy to fill gaps in domestic supply chain capabilities, while expanding cooperation with partner countries overseas to grow and diversify critical mineral industries at large. Expanded domestic industrial capacity will, in turn, both increase the utility of contemporaneous and future stockpiling efforts and reduce the scale of potential disruptions that such efforts might need to plan for.

Overall, policymakers interested in securing U.S. mineral supply chains should envision a mineral strategic reserve as a versatile market tool by which the government actively buys and sells mineral commodities to support domestic mining and processing projects. Related proposals include an evolution of the Strategic Petroleum Reserve into a Strategic Resource Reserve,[240] a Resilient Resource

Reserve designed around a wholly-owned government corporation,[241] or frameworks articulated in the Critical Materials Future Act[242] (Department of Energy pilot program) and the Securing Essential and Critical U.S. Resources and Elements (SECURE) Minerals Act (wholly-owned government corporation).[243] Such a reserve program playing an active market actor role could conduct entirely financial transactions in theory and need not necessarily handle direct offtake, storage, and sale of purchased materials—though particular commodities and scenarios could favor strategies that involve physical handling. At the same time, military necessities may demand determined acquisition in parallel of certain essential raw materials for the NDS even in the face of robust supply chain headwinds.

Our mineral-by-mineral supply chain analysis in this report can assist planners exploring physical stockpiling as part of either category of efforts. Fundamentally, the decision of whether or not to stockpile a commodity depends not just upon technical and supply chain factors, but upon a clearly defined policy goal for that reservoir of materials.

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