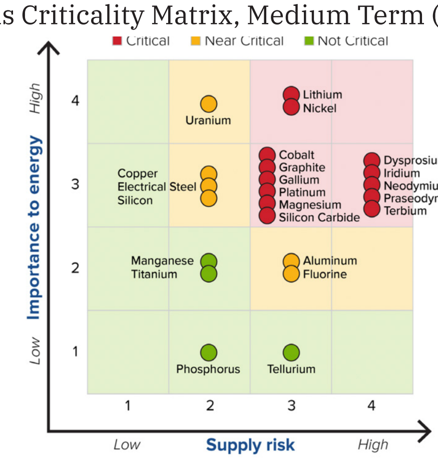
Critical Materials

Minerals are integral to modern society. They are found in alloys, magnets, batteries, catalysts, phosphors, and polishing compounds that are integrated into aircraft, communication systems, electric vehicles, lasers, naval vessels, and electronics and lighting.[1] However, some minerals have limited supply and incur high environmental and financial extraction costs. Given their necessity, concern exists over whether supply can meet future economic needs. Material criticality is assessed by supply risk, vulnerability to supply restrictions, and environmental implications.[2] There are 17 rare earth elements (REEs), many vital for renewable energy and energy storage.[5]

- Global demand for critical materials is expected to rise as the world shifts to clean energy. Demand for lithium and graphite used in EV batteries is forecast to increase 4,200% and 2,500% by 2040, respectively.[3,4]
- Doubling offshore wind capacity compounds demand for rare earth magnets, with new installations growing five- to seven-fold between 2021 and 2035.[6]
- The average amount of critical materials needed to produce a new unit of power generation capacity has increased by 50% since 2010.[3]
- The U.S. produced an estimated 45 kt of rare-earth-oxide (REO) in mineral concentrates in 2024, valued at $260M.[8]

Materials Criticality Matrix, Medium Term (2025-35)[6]

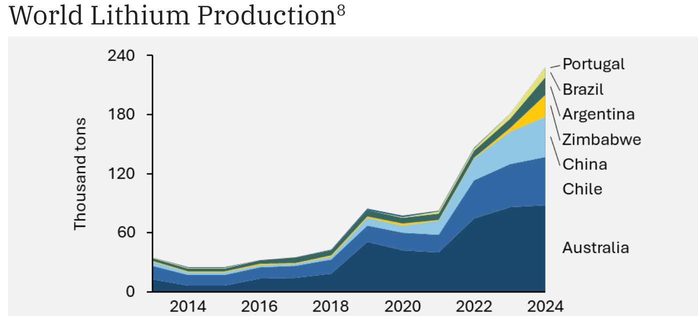


Critical Materials Categories

Energy Critical Elements

- The Energy Act of 2020 defines critical materials and minerals as those that serve an essential function in manufacturing and have high risk of supply disruption, with significant consequences for the U.S. economy or national security.[7]
- In 2022, USGS published a list of 50 critical minerals, including dysprosium, nickel, and platinum.[8] The U.S. is 100% import-reliant for 10 critical minerals and over 75% import-reliant for another 10.[8]
- The 2023 critical materials list published by the U.S. DOE includes 18 critical materials for energy, and 50 critical minerals determined by USGS. Among the DOE's 18 critical materials for energy, 4 are not on the USGS list: copper, electrical steel, silicon, and silicon carbide.[9]
- Critical materials for energy are determined based on short- and medium-term assessment[9] of supply risk and importance to the energy sector.[6]
- DOE identified 7 materials as short-term critical (until 2025): dysprosium, neodymium, gallium, graphite, cobalt, terbium, and iridium. These are used in magnets, batteries, LEDs, hydrogen electrolyzers, fuel cells, and power electronics.[6]
- Over the medium term (2025–2035), nickel, platinum, magnesium, SiC, and praseodymium become critical, primarily for batteries and vehicle lightweighting.[6]
- The DOE's Critical Materials Institute has more recently focused on rare earth materials, battery materials (lithium, cobalt, manganese, graphite), indium, and gallium.[10] DOE strategies for addressing criticality include diversifying supply, developing substitutes, and improving reuse and recycling.[11]
- Energy critical elements (ECEs) are integral to advanced energy production, transmission, and storage. Elements may be classified as energy critical due to crustal rarity, rare economically extractable deposits, or lack of availability.[12]
- 29 possible ECEs were identified: 13 rare earth elements, 5 photovoltaic ECEs, 6 platinum group elements, and 5 others. The U.S. relies on imports for over 90% of most ECEs.[12]
- Photovoltaic ECEs include gallium (Ga), germanium (Ge), selenium (Se), indium (In), and tellurium (Te).[12]
- Platinum group elements are necessary for fuel cells and advanced vehicles.[12] U.S. platinum use increased 39% from 2021 to 2024.[8]
- Platinum and palladium production is concentrated in South Africa (70% and 38%) and Russia (11% and 39%).[8]
- Lithium (Li) is increasingly important for batteries in phones, laptops, and EVs. Bolivia, Argentina, and Chile hold 59.3% of global resources, while Australia, Chile, China, Zimbabwe, and Argentina produced 91% of world lithium in 2024.[8]
- Efforts are underway to extract elements from lower quality resources. Researchers have recently developed a method for extracting lithium, vanadium, and uranium from seawater.[13]

World Lithium Production[8]

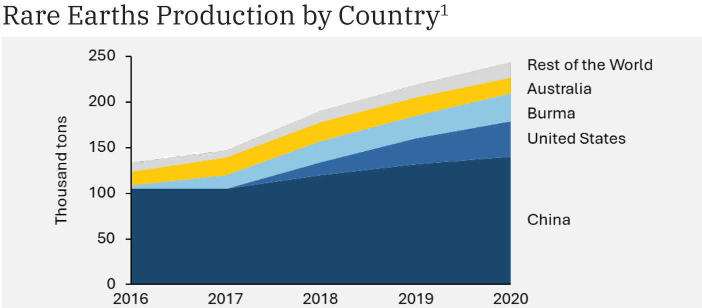


- Copper is key for electrical wiring and appliances.[14] At current production levels, existing resources may last 60 years, with extraction becoming more energy-intensive as ore quality decreases.[14]
- Top producers include Chile (23%), Peru (11%), Congo (14%), China (8%), and the U.S. (5%).[8]
- Copper is unique in that it does not lose its physical and chemical properties when it is recycled;[15] in 2024, 35% came from recycled sources (17% post-consumer, 83% new manufacturing scrap).[8]

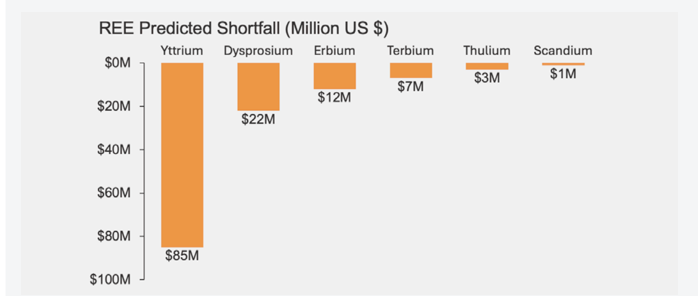
Rare Earth Elements

- REEs are a particularly important group of critical minerals. Although moderately abundant in Earth's crust, they are distributed diffusely and thus difficult to extract in large quantities.[17]
- REEs are used in cell phones, energy-efficient lighting, magnets, EV batteries, and catalysts for automobiles and petroleum refining.[17]
- There are 17 REEs: the lanthanide elements (atomic numbers 57-71), scandium (Sc), and yttrium (Y).[1] The REEs terbium (Tb), neodymium (Nd), praseodymium (Pr), and dysprosium (Dy) are key components of the permanent magnets used in wind turbines.[18] Substitutes for REEs are available but less effective.[8]
- Global mine production increased to an estimated 390 kt of REO equivalent in 2024, largely due to increased mining and processing in China, Nigeria, and Thailand.[8]
- China produced 270 kt of REEs in 2024, 69% of global production, holds reserves of 44 Mt.[8] The U.S. was the second-largest producer with 45 kt and reserves of 1.9 Mt.[8]
- Burma became the third-largest producer with a 217% increase between 2022 and 2023.[23]
- Demand for ECEs, coupled with rising mining standards in many countries, has shifted production to countries with low costs and lax environmental regulations, increasing extraction impacts. However, developing nations naturally contain greater quantities of ECE ore deposits.[12]
- The U.S. used $613M of REEs in 2016, generating $496B in economic activity across other sectors, including oil refining, medical devices, and automotive manufacturing.[4]

Rare Earths Production by Country[1]



REE Predicted Shortfall ($M)[16]



Life Cycle Impacts

- Mining is a destructive process that disrupts the environment and widely disperses waste. Chemical compounds used in extraction can enter the air, surface water, and groundwater.[19]
- Grinding and crushing ore containing critical elements often releases dust with carcinogenic and negative respiratory effects on exposed workers and neighbors.[19]
- Mining can negatively impact human rights. The Democratic Republic of Congo is the world's leading producer of cobalt, widely used in EV batteries, but child labor is routine due to lax regulation and oversight.[20]
- Some REE deposits contain thorium and uranium, which pose significant radiation hazards. While these elements can generate nuclear energy, they are rarely economically recoverable and remain in tailings, posing environmental and human health risks.[12]
- Recycling critical materials results in much lower human health and environmental impacts than mining virgin material. However, improper recycling procedures, often occurring in developing nations with lax or nonexistent worker protection regulations, can lead to exposure to carcinogenic and toxic materials.[19]

Solutions and Sustainable Actions

- Recycle electronics. Metals recovered from cell phones, televisions, and computers can be effectively reused or recycled, though currently less than 1% of REEs are recycled.[21]
- Buy refurbished rather than new products. Rent products from companies with take-back programs requiring material recycling.[12]
- Current legislation expands federal support for domestic mineral extraction, appropriating $5B to the Department of Defense's Industrial Base Fund for critical mineral supply chain investment, plus $2B for strategic stockpiling.[22] However, it leaves some gaps unaddressed, repealing or phasing out measures that would increase processing and midstream capacity building.[22]