We don’t need deep-sea mining

How we can avoid damage to our ocean while meeting critical mineral needs

ENVIRONMENT AMERICA
RESEARCH & POLICY CENTER

U.S. PIRG
Education Fund

FRONTIER GROUP

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Summer 2024

Acknowledgments

The authors sincerely thank Elizabeth Chamberlain of iFixit, Dr. Andrew Dale of the Scottish Association for Marine Science, Sandra Goldmark of the Columbia Climate School and Barnard College, Beth Orcutt, Senior Research Scientist at the Bigelow Laboratory for Ocean Sciences, and Bobbi-Jo Dobush, Legal Officer and Deep Seabed Mining Focal Point at the Ocean Foundation, and Maddie Winter, Program Officer at the Ocean Foundation for their review of parts of this document, as well as their insights and suggestions. Thanks also to Elizabeth Ridlington of Frontier Group and Abigail Ham for their contributions and editorial support.

The authors bear responsibility for any factual errors. The recommendations are those of Environment America Research & Policy Center and U.S. PIRG Education Fund. The views expressed in this report are those of the authors and do not necessarily reflect the views of our funders or those who provided review.

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Cover photo: *Relicanthus* sp.: an anemone-like species found living on sponge stalks attached to nodules on the seafloor of the Clarion-Clipperton Fracture Zone. Credit: Diva Amon and Craig Smith, ABYSSLINE Project, University of Hawaii

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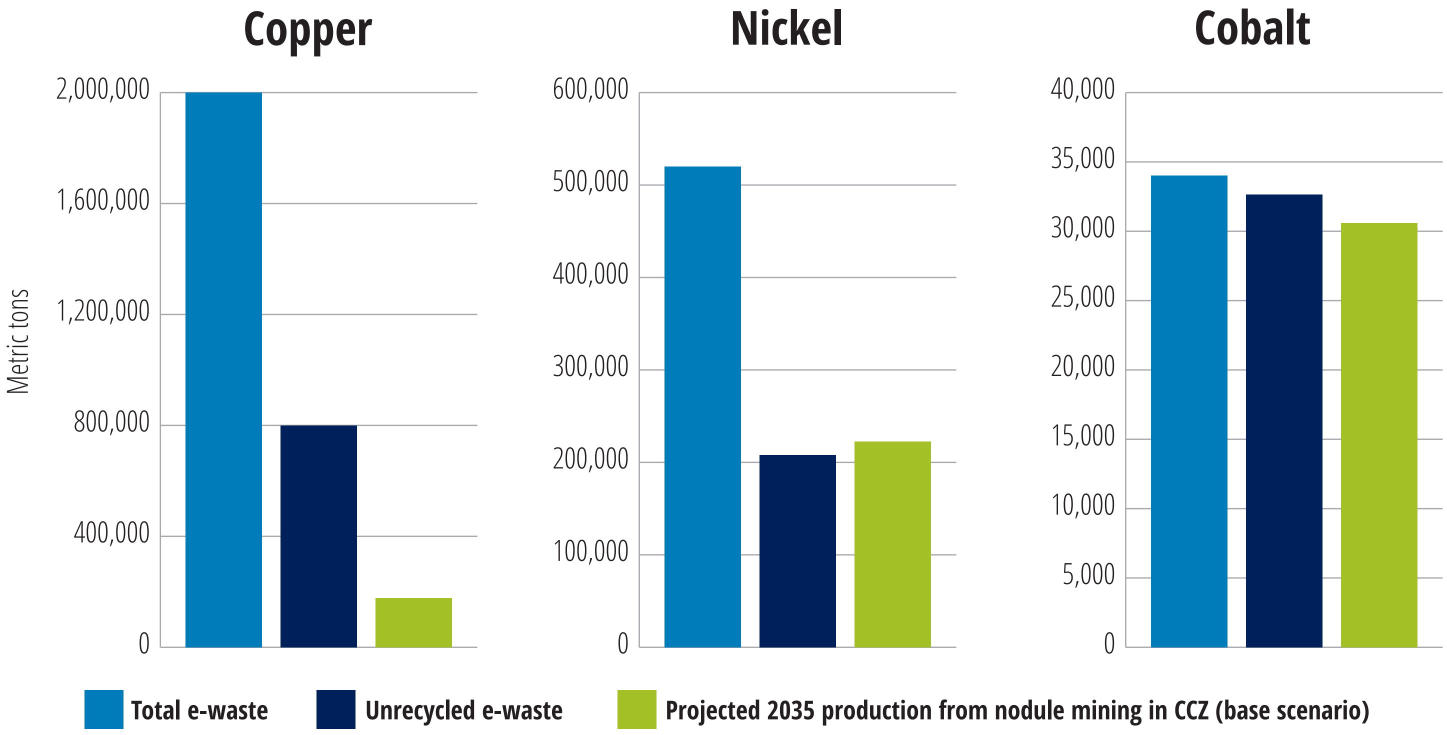
Executive summary

The world is in the midst of a historic transition from fossil fuels to renewable energy from the wind, sun and other sources. The energy transition will help prevent the worst impacts of global warming and mitigate the damage caused by the extraction, processing and transportation of fossil fuels.

No energy source is without environmental impacts, however, and many emerging energy technologies – from wind turbines to electric vehicles – depend on "critical minerals" such as lithium, cobalt, nickel, copper and rare earth elements that are often extracted in damaging ways. Demand for these minerals for fossil fuel-free energy systems is expected to grow dramatically in the coming decades, though forecasts of the extent of that growth vary widely.

The threat of critical mineral shortages is being used to justify entirely new and destructive forms of extraction such as **deep-sea mining** – a form of mining that would jeopardize unique and vital deep-sea ecosystems that science is just beginning to understand as well as the health of the ocean at large.

Figure ES-1. Annual e-waste production vs. projected annual production from nodule mining in Clarion-Clipperton Zone of the central Pacific Ocean (base scenario)[3]



Deep-sea mining is not needed to achieve the global energy transition,[1] and there are many strategies the world can use to reduce the need for new mineral extraction from all sources – including making use of the vast mineral resources in the products we own and the waste we have created. **In fact, the world currently trashes more copper and cobalt in discarded electronic waste each year than would likely be supplied annually by a proposed ramp-up of deep-sea mining in the central Pacific through at least 2035.**[2]

By building a circular economy for critical minerals now – one in which products are built responsibly and to last; fixed when they break; and recycled into new products at the end of their lives – we can reduce pressure for all forms of mineral extraction, including deep-sea mining, and lay the foundation for a sustainable energy system for decades to come.

A circular economy for critical minerals can be built around the "5 Rs" – the traditional 3 Rs of "**reduce, reuse and recycle**," coupled with **reimagining** products for greater efficiency and durability and **repairing** products to extend their lifetimes. These and similar strategies could **fully close any global supply gaps** for nickel and copper by 2030 and dramatically narrow them for cobalt, lithium and the rare earth element neodymium.[4] (See Figure ES-2.)

Deep-sea mining will cause irreparable harm to sensitive and unique ocean ecosystems.

- The deep ocean seabed is a vibrant, biodiverse place, teeming with complex ecosystems and thousands, possibly millions of species, many of which scientists are only now beginning to learn about, and likely many more yet to be discovered.[5]
- Deep-sea mining operations could take place over hundreds to thousands of square miles of seafloor, harming not only species that live along the seafloor, but broader ocean ecosystems as well.[6]
- The plumes of kicked-up sediment and discharged mining waste from deep-sea mineral extraction could have extensive and wide-ranging impacts on ocean ecosystems.[7] Sediment in midwater plumes could travel huge distances from mining sites, potentially affecting an area of several million square kilometers over the course of a 20-year mining operation.[8]

Figure ES-2. **Strategies to reduce demand for critical minerals**

Deep-sea mining is not needed to meet the demand for critical minerals.

- Deep-sea mining is not a potential source of all the critical minerals required for the clean energy transition. Cobalt, nickel, manganese and copper are the minerals believed to be available in the greatest abundance in deep-sea deposits, with more limited potential for lithium and rare earth elements.[9] Other key energy transition minerals, such as graphite, are not available in deep-sea deposits at all.
- The amount of critical minerals needed for the energy transition is highly uncertain, with recent forecasts of growth in cobalt demand in 2040 varying by more than a factor of 12, and forecasts of demand for other key minerals often varying by a factor of four or more.[10]
- Deep-sea mining is unlikely to play an important role in mitigating near-term shortages of critical minerals. Deep-sea mining can likely only make a meaningful near-term impact on markets for nickel and cobalt – two metals that are likely to have sufficient supply to meet near-term demand and for which long-term demand is especially uncertain given the rapid evolution of battery technology.[11] Given the doubts remaining about the technological and economic viability of deep-sea mining and the regulatory regime under which it will operate, **the world cannot rely on deep-sea mining for the energy transition.**[12]
- Deep-sea mining would not necessarily lead to a reduction in land-based mining. There are sufficient land-based minerals to support the clean energy transition, and entities are unlikely to change current plans for land-based mining to accommodate the uncertain future prospects of deep-sea mining.[13] **The best way to protect the environment and communities from land-based mining is through stronger mining regulation and reducing demand for minerals, not opening up new frontiers for mineral exploitation.**

Building a sustainable circular economy on the foundation of the "5 Rs" can help to alleviate needs for newly mined critical minerals in both the short-term and long-term.

- The International Energy Agency estimates that a combination of recycling, the use of smaller electric vehicle batteries and the adoption of alternative battery chemistries could reduce demand for lithium by as much as 25% by 2030, while recycling can reduce the demand for newly mined copper and cobalt by 30%, and lithium and nickel by 15% in 2040.[14]

America and the world possess vast stocks of critical minerals in the products we use, the waste we create, and the residues from mining and industrial processes – resources that we can tap to reduce the need for new mining in the deep ocean.

- Electronic waste is rich in critical minerals. Globally, 62 million metric tons of electronic waste was created in 2022, of which only 22% was properly recycled.[15] The electronic waste the world produced in 2022 contained enough copper to meet 14% of the forecast annual global energy transition demand in 2035; 31% of 2035 energy transition demand for nickel; 13% of cobalt demand; and 12% of neodymium demand.[16] At least 3 million metric tons of unrecycled e-waste was created in the United States alone – an important, untapped, domestically available source of valuable minerals.[17]
- Vast amounts of critical minerals – especially copper and nickel – are also in use elsewhere in the economy. Extending the lifetimes of products using those metals and recycling them at the end of their lives can reduce pressure for new mining. In addition, waste from mining and industrial processes often contains critical minerals. The U.S. Department of Energy estimates that coal ash from U.S. power plants contains an estimated 172,000 tons of neodymium – enough to supply more than two years of global demand in the mid-2030s – along with 288,000 tons of lithium, 252,000 tons of nickel and 110,000 tons of cobalt.[18]

Eliminating "disposable" electronics and extending the lifespan of products already in use can reduce the strain on critical mineral supplies and the need for additional destructive mining – including in the deep ocean.

- The most immediate difference consumers, manufacturers and governments can make to address short-term mineral supply concerns is to extend the life of existing products containing critical minerals and end the use of disposable electronics. Doubling the lifetime of a product can reduce demand for materials by as much as 50%, while increasing product lifespans by half can reduce demand by as much as one-third.
- Opportunities include:
    - **Consumer electronics –** Electronic products such as earbuds, smartphones, e-cigarettes and laptops include critical minerals such as rare earth elements and copper. Yet, many of these electronics have short lifespans – from a few years in the case of smartphones and laptops to a few days for disposable e-cigarettes. Extending the lifespans of these products can reduce the need to replace them – freeing up valuable critical mineral supplies for the energy transition.
    - **Energy transition technologies –** The first generation of solar panels, wind turbines and electric vehicles are now reaching the end of their useful lives, and while their numbers are small in comparison to the dramatically rising volumes of these technologies being deployed now, extending their lifetimes can alleviate some critical minerals demand in the short run and pave the way for a circular economy in the future. **Second-life** applications, which reuse electric vehicle batteries and solar panels when they are no longer able to fulfill their primary purpose, are particularly promising options.
    - **Other products –** Critical minerals are in use in a wide variety of other products – from MRI machines to stainless steel. An economy-wide effort to encourage product repair and lifespan extension can reduce demand for these materials elsewhere in the economy, freeing them up for the energy transition.

America should work to alleviate short-term critical mineral challenges by tapping the ample domestic resources available in products and e-waste, while working to build a circular economy for energy transition metals without deep-sea mining. The following are among the most important steps the nation should take:

- The U.S. Congress should institute a precautionary pause or moratorium on seabed mining in U.S. territorial waters and on processing of minerals obtained by seabed mining in U.S. states or territories. The U.S. should also provide diplomatic support for efforts to adopt a precautionary pause or moratorium on deep-sea minerals production in international waters, joining roughly two dozen other countries in calling for a delay in deep-sea mining.[19]
- State and federal governments should adopt "right to repair" legislation to make it easier to fix the stuff we use; ban disposable and irreparable small electronics such as disposable vapes; create standards to help consumers identify more durable and fixable products, thus incentivizing manufacturers to produce longer-lasting products; and encourage "second-life" applications for clean energy technologies approaching the end of their useful lives.
- Governments should invest in improved standards and infrastructure for recycling, especially for e-waste; investigate opportunities for environmentally responsible use of industrial waste streams for critical minerals; and take steps to make every part of our economy more energy efficient and less material intensive.
- Governments should improve environmental protections for terrestrial mining; and governments, companies and consumers should advocate for the adoption and enforcement of global standards for environmental and social responsibility in mining.[20]

Deep-sea mining puts sensitive ocean ecosystems at risk

There are many possible approaches to meeting the demand for critical minerals for the energy transition – including strategies that reduce the growth in mineral demand through smart product design, increase recycling of products that contain critical minerals, and tap mineral-rich sources of waste from previous industrial activities.

Rather than maximize these more sustainable sources of minerals, mining companies and some governments around the world are instead seeking to open up a brand-new front for mineral extraction: the deep sea. Opening the deep sea to mineral extraction would imperil vulnerable species – including many that science has yet to discover – while jeopardizing the ocean's ability to provide a healthy source of food and store carbon.

What is deep-sea mining?

The presence of large stores of minerals in the deep ocean has been known for more than half a century. The possibilities for commercial harvesting of these deposits – which include valuable metals such as zinc, cobalt, copper, nickel and gold – were being discussed as far back as the 1970s, but only in the last few years has large-scale extraction of these resources come to be considered a realistic possibility.[21]

Advances in deep-sea technology and growing demand for the metals now known to exist in abundance on the ocean floor, such as cobalt and nickel, have led to renewed attention and investment in deep-sea mining.[22] While the technological and economic viability of this expensive and complex form of resource extraction are still unclear, interest in large-scale seafloor mining is on the rise.

The largest deposits, of the most interest to deep-sea mining advocates, take three forms:

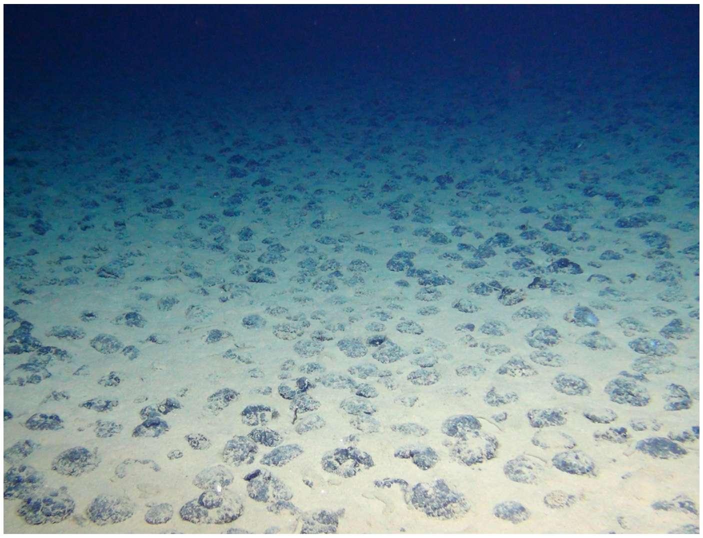
A note on terminology

In geological terminology, the deposits currently of most interest to mining advocates are referred to as **ferromanganese nodules**, **hydrothermal sulfides** and **ferromanganese crusts**. When described as "resources" in economic terms, ferromanganese nodules are referred to as **polymetallic nodules**, hydrothermal sulfides as **polymetallic sulfides**, and ferromanganese crusts as **cobalt crusts**.

Ferromanganese nodules

Current interest in deep-sea mining is focused mainly on ferromanganese nodules, also called "polymetallic nodules": small, potato-size mineral accretions formed on the ocean floor.[23] These deposits contain multiple metals, such as cobalt, copper, nickel and manganese, as well as rare earth elements and other minerals.[24]

Nodule accumulations exist across vast areas of the abyssal plain – flat areas of seafloor at depths of between 3,000 and 6,000 meters.[25] Current commercial exploration is focused on four geographic



Polymetallic nodules on the ocean floor of the Clarion-Clipperton Zone. Credit: Wikimedia commons, user Mister Pommeroy, CC-BY-4.0-DEED

regions in particular: the Penrhyn Basin in the south-central Pacific; the Peru Basin in the south-east Pacific; the center of the north Indian Ocean; and, most of all, the 1.7 million-square-mile Clarion-Clipperton Fracture Zone (CCZ) in the north-central Pacific.[26]

The Clarion-Clipperton Zone nodule field is the largest of the known fields, both in geographical area and the mass of nodules it contains.[27] By one estimate, a square meter of ocean floor in this zone contains on average around 15 kilograms (33 pounds) of nodules, and in some cases up to 75 kilograms (165 pounds).[28] A 2022 study estimates the total mass of nodules in the CCZ nodule field as around 21.1 billion tons, noting that this figure is itself a conservative estimate.[29]

Hydrothermal sulfides

Hydrothermal sulfides, also known as polymetallic sulfides, are formed through hydrothermal vent activity near mid-ocean ridges where tectonic plates are moving apart, which releases superhot, mineral-rich water into the surrounding ocean.[30] Heated by magma beneath the Earth's surface, the water picks up dissolved minerals as it travels through the oceanic crust, and when this water meets the cold seawater, it precipitates minerals, forming chimney-like structures.[31] Where this activity has occurred over long periods of time, there can be thick deposits of these sulfides under the seafloor.

These deposits contain high concentrations of valuable minerals, including metals such as copper, gold, silver, zinc and rare earth elements. Deposits at a single vent can contain millions of metric tons of ore.[32]

Ferromanganese crusts

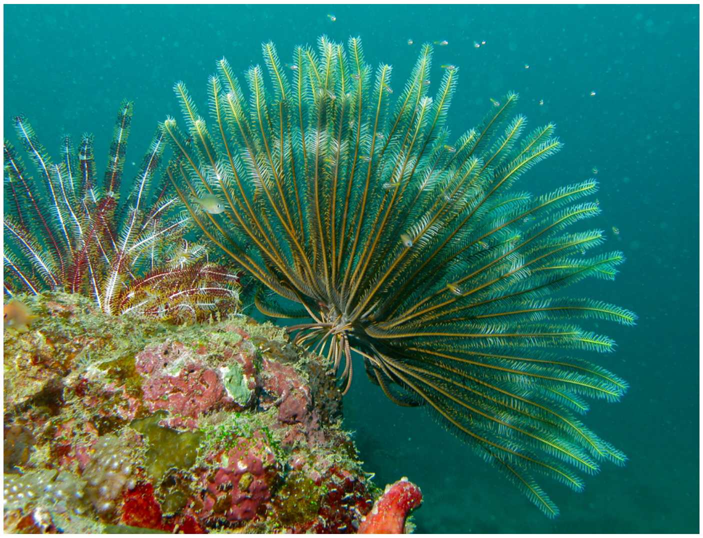
Ferromanganese crusts, also known as "cobalt crusts," are deposits formed over the course of millions of years on the surfaces of seamounts and other hard substrates on the ocean floor, containing cobalt, nickel, copper and rare earth elements.[33] The Pacific Ocean Prime Crust Zone, thought to be the region containing the greatest quantity of crust deposits, is estimated to hold around 7.5 billion dry tons of cobalt-rich ferromanganese crusts. These deposits are thought to hold greater quantities of certain elements than any terrestrial reserve, but these estimates are based on few actual measurements.[34]

Deep-sea mining is a threat to the ocean

The deep ocean where these untapped resources lie is known to be a vibrant, biodiverse place, teeming with complex ecosystems and thousands, possibly millions of species, many of which scientists are only now beginning to learn about, and likely many more yet to be discovered.[35]

The extreme conditions and relative inaccessibility of the regions of ocean of most interest for commercial mining have led to a lack of scientific research on this last great wilderness. Hence, the nature of the habitats, species and ecosystems that will be impacted by mining is only just beginning to be understood.[36] Recent research, however, has indicated both the wealth of biodiversity in deep-sea habitats and how much we have yet to learn about it. One 2023 study, for example, identified more than 5,000 as-yet-unnamed marine species in the Clarion-Clipperton Zone alone.[37]

The ocean's abyssal plains, where most of the current international interest in deep-sea mining is focused,



Featherstars. Credit: Bernard Dupont, via Wikimedia Commons

are the largest habitat on the planet.[38] Characterized by soft sediment, mainly composed of clay, silt, and the remains of marine organisms, their unique conditions provide habitat for organisms adapted to extreme depths, high pressures, darkness and cold temperatures.[39] Waters of the abyssal plains are some of the clearest seawater on Earth, since there is very little particulate matter raining down from the surface ocean.[40] The diverse wildlife that inhabits these and other parts of the deep ocean of interest to mining advocates includes deep-sea fish (some of which, like the black oreo, orange roughy and sablefish, can live to be a century old or more); invertebrates (such as sea cucumbers and deep-sea corals and sponges); a wide variety of snails, mussels, clams and worms; and the diverse microbial life that forms the basis of marine food webs, allowing other species to thrive.[41]

These vast, flat plains are punctuated by hills, valleys, seamounts, underwater mountain ranges and other topographical features, many of which are hotspots for biodiversity.[42] A 2015 study of abyssal hills, for example – small hills that rise from the floor of an abyssal plain – found an astonishing array of life: arthropods such as squat lobsters and sea spiders, stalked sea squirts, a variety of deep-sea anemones and sea cucumbers, starfish and their relatives brittle stars (also known as serpent stars), crinoids (a class of invertebrates including sea lilies and feather stars), spoon worms, sponges, single-celled planktonic animals, and a number of unknown species.[43]

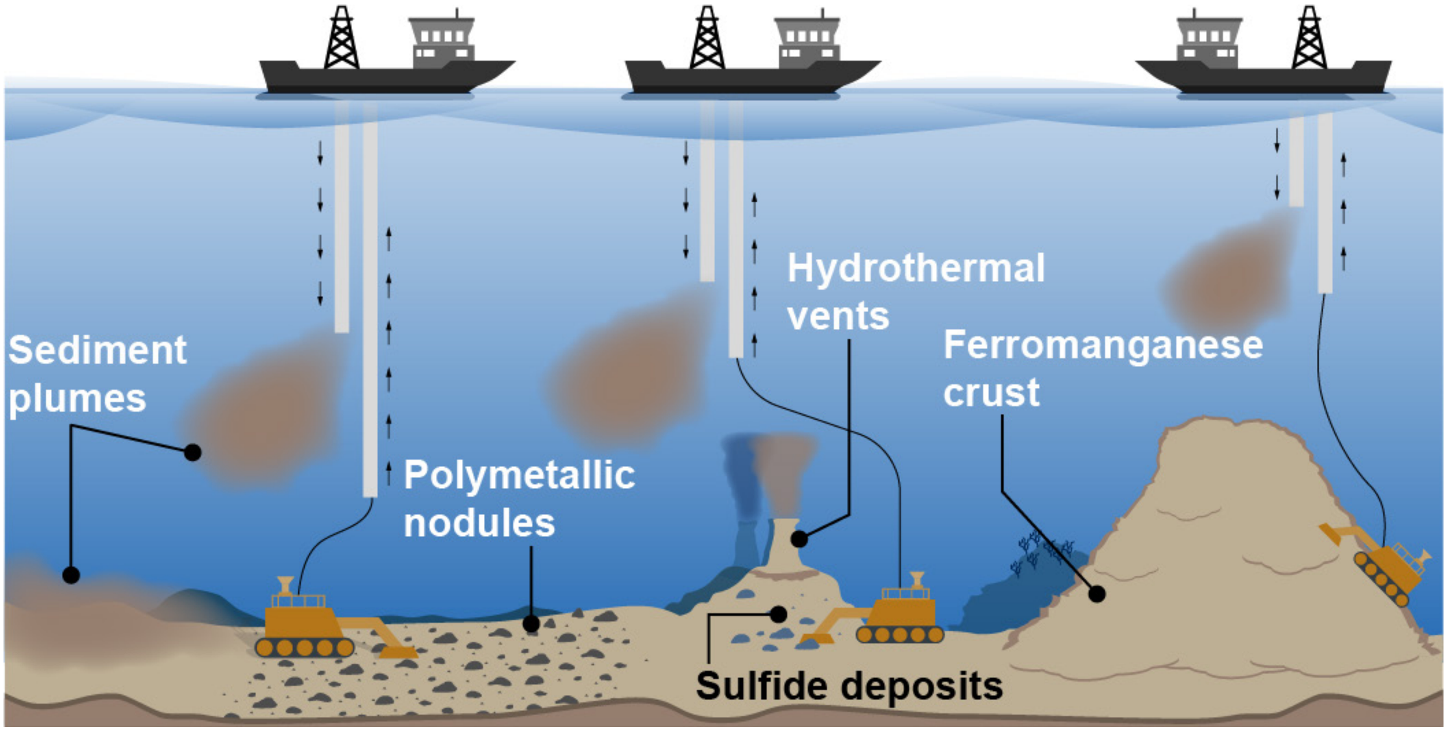
The full extent of the damage mining operations will inflict on this mysterious and still largely unexplored underwater world has likewise yet to be definitively established. However, a growing body of research indicates that disturbing these delicate environments will cause substantial, and most likely irreparable harm to marine species and ecosystems – both at the mining sites themselves and across hundreds, and potentially thousands of miles of surrounding ocean.[44]

Impacts to the mining area

Deep-sea mining could take place in various parts of the deep ocean, with different types of mineral resources being targeted depending on the geological characteristics of each region. Each of the three main areas of interest for commercial mining is teeming with its own unique habitats and ecosystems, and mining in each of these areas will inflict its own specific set of harms, with long-lasting and, in some cases, likely irreversible effects on the biodiversity and structure of ocean habitats.

To be economically viable, deep-sea mining will likely need to take place on a huge scale. By one estimate, for a nodule operation to be financially viable it would have to mine around 400 square kilometers (150 square miles) of seabed every year – an area roughly the size of Philadelphia.[45] Others have suggested 300 square kilometers (around 120 square miles) per year.[46] Another projection suggests that a single operation would mine roughly 8,000 to 9,000 square kilometers (3,000 to 3,500 square miles) over a 30-year mining license period.[47] Another has calculated that, in the approximately 29,000-square mile (75,000-square kilometer) area of the CCZ in which Germany has been licensed to conduct mining exploration, roughly 2.2 million tons of nodules would have to be extracted for the mining to be commercially viable.[48] In short, while assessments of its profitability vary, there is broad agreement that for deep-sea mining to be

Figure 1. Types of deep-sea mining (Illustration: U.S. Government Accountability Office)[49]



financially worthwhile, its ecological footprint would have to be enormous.

Most obviously, the damage to ocean ecosystems would stem from the fact that mining operations disrupt substantial areas of the ocean floor, and therefore the species that rely on it for their habitat.

Nodule mining

Extraction of ferromanganese nodules from the seabed is currently carried out by remotely operated vehicles and mining machines equipped with cutting and suction tools to vacuum up nodules from the seafloor. Propelled by caterpillar tracks (like those of tanks or bulldozers) and weighing up to 250 metric tons, these giant machines drive across the seabed, cutting or sucking up the nodules, which are then piped up to the surface with pumps or riser systems and transferred to a surface vessel for processing.[50] Trials of a 70-ton-plus prototype of one of these vehicles by The Metals Company in 2022, one of which ripped up around 4,500 tons of nodules from an 80-kilometer-long stretch of the Pacific Ocean floor, have been hailed as a success by the company, and this system is now set to be scaled up for future trials.[51]

This highly destructive process would impact large areas of sensitive habitat.

- A 2016 survey of four sites in the eastern Clarion-Clipperton Zone similar to the ones currently in the sights of deep-sea mining advocates found a large degree of habitat diversity compared with other areas of the abyssal plain, and with it, a diverse array of life, with 170 distinct types of megafauna found in one 30-square kilometer study area.[52]
- These organisms include brittle stars, sea anemones, sponges and deep-sea corals.[53] Of the 12 metazoan species collected during the study, seven were previously unknown to science, including three new genera (the taxonomic category just above species).[54]
- A study published in 2016 comparing creatures associated with ferromanganese nodules in four areas of the Clarion-Clipperton Zone with different levels of nodule coverage found that densities of epifauna (creatures that live attached to hard surfaces such as rocks) are more than twice as high in dense nodule fields as in areas with few or no nodules, and that

some organisms, including certain soft corals, are "virtually absent" from nodule-free areas.[55]

- The nodules themselves support diverse habitats and organisms. In the 2016 survey mentioned above, roughly half of the types of organisms identified were found exclusively on the nodules.[56] Species associated with nodules include actiniarians (a genus of sea anemones); alcyonacean corals (commonly known as soft corals) and antipatharian corals (black or thorn corals); and hexactinellid sponges (also known as glass sponges).[57] These structure-forming species often play an important role in creating habitats for other animals that depend on seafloor areas for part or all of their lifecycle.

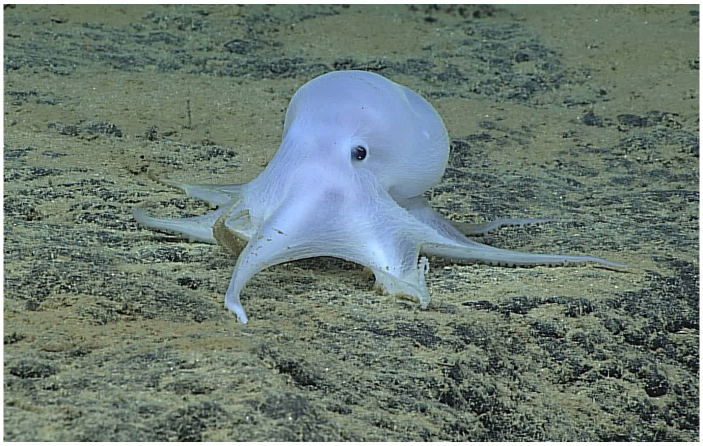
The organisms that live on polymetallic nodules are linked to the rest of the marine ecosystem up the water column to the ocean surface and contribute to the health of the wider ocean.[58]

- Nodules play a key role in the marine food web. A 2021 study of the CCZ and the Peru Basin concluded that taking out key "compartments" of the food web (in particular, disrupting interactions between nodules and the organisms attached to them, and between those organisms and their associated fauna) would have cascading effects throughout the food web, likely resulting in reduced biodiversity on and near the seafloor in the surrounding area.[59]

Nodule mining is by its very nature a destructive process that would do major damage to large areas of sensitive habitat. In much of the deep ocean, hard surfaces like those of ferromanganese nodules are valuable real estate for sessile ocean creatures, providing irreplaceable habitats, including for creatures that themselves play a key role in creating habitats for other organisms and thus structuring marine ecosystems.

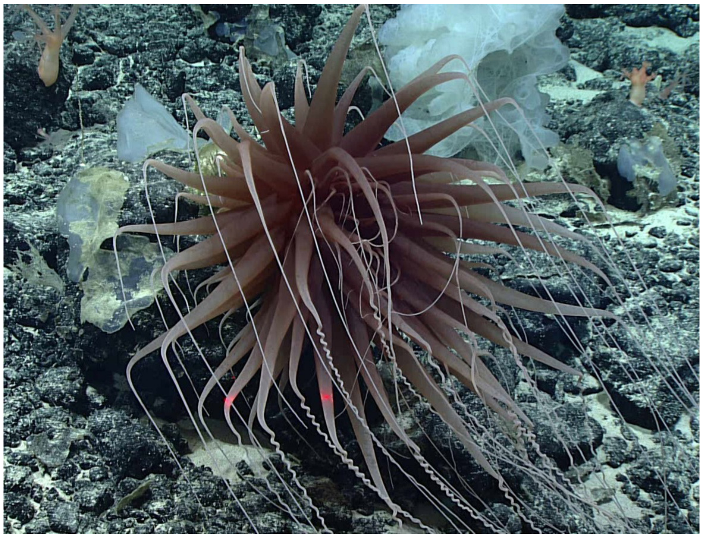
Crusts and seamounts

Cobalt-rich ferromanganese crusts form on submerged rock surfaces, most commonly on the rocky flanks and summits of seamounts – underwater mountains rising 1,000 meters or more from the ocean floor.[60] The thickest and most cobalt-rich crusts are found at depths of 800 to 2,500 meters on the sides of underwater mountain ranges and seamounts in the western Pacific.[61] A recent study highlights that a large fraction of seamount habitats in this region have already been licensed for mining exploration, with little remaining for targeted protection.[62] Mining operations targeting these crusts would typically involve deploying dredges or hydraulic suction systems to remove the crusts from the seabed and transport the collected crusts to a surface vessel for processing.



Recent research indicates that ferromanganese nodules are important breeding grounds for these newly discovered deep-sea octopods nicknamed "Casper," due to their likeness to the friendly cartoon ghost. Credit: NOAA Office of Ocean Exploration and Research.

Glass sponges. Source: NOAA/OAR/OER, from a 2016 Deepwater Exploration of the Marianas



Relicanthus daphneae - giant sea anemone. Source: NOAA.

As with nodule extraction, these processes put vulnerable marine habitats and wildlife communities at risk.

- Studies of ferromanganese crusts have found highly diverse communities of many species, particularly filter-feeders, adapted to the seamount habitats where these crusts are found.[63] National Oceanic and Atmospheric Administration surveys of these areas have found thriving populations of corals, sponges and other invertebrates.[64]
- Seamounts support a rich array of life, including deep-sea corals, fishes, cephalopods (octopi, squid, etc.), turtles, marine mammals and others.[65] These unique environments attract major aggregations of sharks, seabirds and marine mammals, and are hubs of biodiversity for pelagic fish (i.e., fish that inhabit the upper zones of the open sea).[66] Their rocky surfaces provide ideal conditions for corals and sponges, and the ecosystems they support generally contain a particular abundance of suspension feeders, such as corals, and benthic filter-feeding organisms.[67]
- These creatures are, in many cases, important to the broader marine ecosystem. Corals and sponges, for example, are a food source for predators and provide habitat for many other species, including crabs, squat lobsters and sea stars.[68] Deep-sea filter-feeding organisms function as a vital link in enabling energy and matter to flow between the deep-water and shallow-water parts of the ocean ecosystem.[69] And so on.
- Seamount habitats are also thought to be important in fostering "speciation" – the process by which populations of a given species evolve to become distinct species – in the deep ocean, and potentially therefore play an important role in maintaining biodiversity in the deep sea.[70]

Sulfide mining at hydrothermal vents

The superheated water ejected by active hydrothermal vents enables a unique ecosystem to thrive in the darkness of the deep ocean environment. These vents and their surroundings are home to a diverse array of life, with more than 500 hydrothermal vent species currently known to science, including tube worms, crabs, fish and microorganisms adapted to the hot, dark conditions in the areas around vents.[71] These species tend to be endemic to these areas and can only survive in the unique conditions these habitats provide.[72] Since research into these habitats is still in its relatively early stages, current knowledge of the extent of the biodiversity they support is almost certainly just the tip of the iceberg, and scientists expect many more species to be discovered as more vent fields are discovered.[73]

The species that live among sulfide deposits created by past hydrothermal activity are even less well-studied than those surrounding active vents.[74] It is these deposits that are currently the main focus of deep-sea mining interest.[75]

Very little data exists on the ecosystems around these deposits, but research suggests that they support a range of flora and fauna.[76] Organisms that rely on inactive deposits are typically "sessile [i.e., attached to rocks or the seabed] filter-feeding, long-lived and slow-growing," and potentially include sponges, corals, anemones, squat lobsters, hydroids (a life stage of hydrozoa – small predatory animals related to jellyfish), ophiuroids (also called brittle stars or serpent stars – echinoderms closely related to starfish) and holothurians (more commonly known as sea cucumbers).[77]

The current absence of knowledge about the ecology of seafloor hydrothermal sulfide deposits means that mining operations in these areas would likely damage or destroy ecosystems and habitats before we have had the chance to properly study them, and potentially even wipe out species we don't yet know exist.[78]

Effects beyond the mining area

While the full extent of the ecological damage likely to be inflicted by deep-sea mining is difficult to predict with the scant information currently available, it can reasonably be assumed that the direct removal of habitat – sucking up nodules, stripping the outer layers of seamounts, and so on – will destroy many of the organisms living directly on the materials being mined. Many of these organisms are found nowhere else on the planet, and some take so long to grow that their destruction could functionally spell extinction.[79]

The impacts of mining will not be limited to the mining sites, however, nor the harms it inflicts confined to the species directly associated with these localized habitats.[80] The process of mining the sea floor generates sediment plumes with the potential to affect sea life well beyond the area being mined.

Two types of plumes are potentially created when mining the seafloor:

- The **collector plume** (also called "benthic plume") on and close to the ocean floor, created by the mining vehicles and machinery.[81]
- The **discharge plume** (also called the "sediment plume" or "tailings plume") in midwater. This consists of wastewater containing sediment and mine tailings (also known as mining "fines") discharged back into the ocean.[82] The process of mining seafloor polymetallic sulfides and ferromanganese crusts entails crushed or ground ore from the mining sites being diluted with large quantities of water and pumped up to a surface vessel as a slurry for processing. The same is true of nodules, although they may also be sucked up whole.[83] On the surface vessel the slurry or nodules are "dewatered," and unwanted products – comprising wastewater containing sediment from the crushing of the mined materials – are pumped back into the ocean, creating these midwater sediment plumes.[84]

These plumes carry harmful substances, sediment and other pollutants, and midwater plumes in particular can potentially carry contaminants significant distances beyond the mining sites.

- A 2021 modeling study estimated that a nodule mining operation in the CCZ could discharge 120,000 metric tons of sediment and 61,000 metric tons of fines each year. The midwater plumes created by those discharges could travel more than 1,000 kilometers in every direction from the mining site over the course of a single 20-year mining operation, the study predicts, potentially spreading sediment over an area of several million square kilometers (roughly the size of the entire CCZ), though the study does not come to any conclusions about the potential impact on ecosystems.[85]
- The turbulent and unpredictable nature of deep-sea currents makes it impossible to predict with any certainty where and how far plumes from a mining site will spread and thus take steps to mitigate potential impacts.[86]

Both collector plumes and midwater plumes carry **sediment** that can kill marine animals:

- Sediment can suffocate and starve marine wildlife, for example smothering suspension feeders such as cold-water corals and sponges on the ocean floor around mining sites.[87]
- Suspended sediments could starve filter-feeding organisms by clogging their filtration apparatus, as would be the case with "flux feeders" such as pteropods – a family of pelagic sea snails and sea slugs, including sea butterflies and sea angels – and copepods (crustacean zooplankton).[88]

- Given the importance of these species (and others potentially affected in similar ways by sediment clouds, such as deep-sea zooplankton) to the marine food web, starvation and reduced growth rates among these species would likely have cascading effects throughout the ecosystem.[89]

As well as creating clouds of suspended sediment, extracting minerals from the ocean floor and the discharge of midwater plumes will release potentially **toxic substances** into the ocean, including chemicals and waste products from mining operations.[90]

- Deep-sea ore deposits themselves consist of naturally occurring mixtures of potentially toxic elements, which may be released into the ocean at various stages of the mining process, including on the ocean floor and in wastewater discharges from surface vessels.[91]

- A 2020 review of literature assessing the impacts of deep-sea mining concludes that sulfide-rich ores could leak "significant amounts" of potentially toxic metals, including compounds known from previous studies of mine tailings to have "acute or chronic adverse effects" on marine wildlife.[92]

- Despite claims from mining advocates that toxicity levels from waste discharges would not exceed thresholds for harm to marine species, the reality is that there has simply not been enough research done to be able to make that claim.[93] The absence of research into how different species will react to toxic discharges makes it impossible to establish safe levels of toxicity for the myriad organisms likely to be impacted by mining.[94] A picture is emerging, however, from studies of individual species. For example, experiments with the cold-water coral *Dentomuricea meteor* found significant mortality after exposure to ground particles of polymetallic sulfides. After 27 days exposure, 95% of the coral nubbins were dead.[95]

- The 2020 study referenced above concluded that sufficient evidence exists to be able to predict that introducing high concentrations of naturally occurring metals into the water column will result in increased mortality, inhibition of growth and/or lower rates of reproduction in the wildlife communities impacted, and moreover that these harms will likely extend further afield through species migrations, and, when they build up in the food chain, to higher trophic levels.[96]

The midwater ecosystems threatened by these toxic discharges are vital to the health of the ocean, playing a key role in connecting the deep ocean with ecosystems closer to the surface, and also play a key role in – among other things – the ocean's ability to absorb carbon from the atmosphere.[97] Importantly, not least for the estimated 3 billion people who rely on fish as a protein source, midwater ecosystems are also home to the largest fish stocks.[98] A buildup of heavy metals and other pollutants in the food chain could lead to **contamination of seafood** and thus pose risks to human health.[99] And by removing food sources for fish (such as plankton and other small organisms), the impacts of mining may deplete fish stocks themselves.[100]

Other impacts to the wider ocean

The plants and animals that live in the deepest regions of the ocean are adapted to extreme and very specific conditions. Disruption to the delicate equilibrium on which they depend could potentially have severe repercussions. For example:

- **Changes to water temperature:** Streams of water discharged at the ocean floor during the extraction process can increase the temperature of the surrounding water, and the process of transporting the mined ore to the surface vessel for processing, as well as the processing itself, can warm the upper parts of the water column.[101] Research has suggested that these discharges of warm water in the deep ocean in particular will harm or kill the creatures subjected to them, many of which depend on cold and stable temperatures.[102]

- **Noise pollution:** Introducing noise – from surface vessels, mining vehicles and other machinery – to naturally silent habitats could have serious impacts on species that use sound or echolocation to navigate, communicate, hunt prey and evade predators.[103] Sound travels faster in the ocean than through air, and across great distances, and organisms that rely on sound – such as whales and dolphins – are extremely sensitive to acoustic changes.[104] By one estimate, noise from a single mining operation could reverberate as far as 500 kilometers, hindering marine animals' ability to communicate, hunt prey and evade predators.[105] Moreover, noise from deep-sea mining operations would likely be near-constant as long as mineral production continues, rather than a temporary disruption.[106]

- **Light pollution:** Just as deep-sea organisms have evolved to live in the silence of the deep ocean, so too have many evolved to live in a naturally dark environment. Most of the organisms that live in the deepest parts of the ocean are adapted to the darkness and have reduced visual capacities and highly sensitive vision, and could therefore be easily disturbed by artificial light, such as from collector vehicles and equipment.[107] Artificial light can also potentially create problems for seabirds and mammals who depend on cycles of light and dark for (e.g.) navigation.[108]

  Conversely, the *reduction* of light by thick sediment plumes can also cause problems for marine wildlife.[109] Many deep-sea organisms emit light (known as bioluminescence), and this light is critical to their ability to communicate.[110] By muddying the waters and impeding the transmission of light, the sediment plumes created by mining operations may hinder these creatures' ability to find mates and therefore lead to lower reproduction rates, hence impacting on species populations.[111]

Can the ocean recover?

Many of the species likely to be harmed by deep-sea mining are long-lived, have slow growth rates and are slow to reproduce. Certain corals, for example, live between 450 and 4,265 years, and some sponges up to 11,000 years – the oldest living creatures known to science.[112] Ferromanganese nodules themselves grow only a few millimeters every million years, and since the species that live on them are long-lived and slow to reproduce, mining these areas will mean the ecosystems they support, and in particular the sessile organisms that live on the nodules themselves, will be effectively gone forever.[113]

A study by the German project Disturbance and Recolonization (DISCOL) plowed a several-square-kilometer area of ocean floor in the Pacific with experimental mining equipment and monitored its recovery. The study found that it took seven years for the area to recover to the same density of bottom life as before, but even then, some species had permanently disappeared – particularly those that depended on a hard substrate.[114] Looking at just one site, moreover, this study does not account for the fact that the damage would be multiplied by the cumulative impacts of multiple mining operations.[115]

Short-term, localized monitoring is also unable to predict the impacts to the wider ocean or those impacts that may unfold over a longer timescale. Destruction or fragmentation of habitats could lead to genetic isolation and reduced connectivity among wildlife populations, for example, leading to reductions in species populations and potentially hindering the evolutionary processes necessary for species to adapt and survive in changing environments. Some scientists have warned that by altering the geochemistry of the sediment on the ocean floor – which could take decades, at least, to recover – mining could cause fundamental changes to the geochemical foundations of marine life.[116] The ecological impacts of disrupting the connectivity (e.g., the flow of energy and nutrients) between the deep ocean and surrounding ocean are likewise unknown.[117]

Deep-sea mining is not needed to meet the demand for critical minerals

Transitioning to renewable energy will almost certainly require increases in the production of many so-called critical minerals. There is, however, tremendous uncertainty about how much and how quickly that production will need to expand, with forecasts of growth in demand for some critical minerals varying by an order of magnitude or more.

There is widespread agreement, however, that deep-sea mining is not necessary to meet demand for critical minerals. The commencement of deep-sea mining would not eliminate the threat of terrestrial mining. And, as will be discussed later in this report, common-sense measures to create a circular economy, including in energy transition minerals, can reduce the need for all forms of extraction – including deep-sea mining – in the years and decades to come.

Critical minerals are necessary for the energy transition

The United States and the world must achieve swift and deep reductions in emissions of carbon dioxide and other greenhouse gases to prevent the worst impacts of global warming. Low-carbon energy technologies – from electric vehicles to solar panels to wind turbines – can help us to break free from our dependence on extracting and burning fossil fuels, which harms the health of people, wildlife and ecosystems around the globe.

No energy technology is without environmental impacts, however, and the transition to renewable energy is expected to bring with it an increase in demand for the critical minerals that are essential to making those technologies work. Extracting and supplying those minerals also has the potential to harm people and ecosystems around the world.

Why are radical new forms of resource extraction such as deep-sea mining being proposed to meet demand for critical minerals? Answering that question begins with understanding what critical minerals are and the role they play in the energy transition.

What are "critical minerals"?

Critical minerals for energy are those that, as defined by federal law, have "high risk for supply chain disruption" and "[serve] an essential function in one or more energy technologies."[118] In the context of the clean energy transition, critical minerals are those that are required in technologies that substitute for fossil fuel production and use – such as wind turbines, solar panels, electric vehicles, hydrogen electrolyzers and other technologies – as well as the infrastructure needed to support their integration into the energy system.

The following are generally considered to be "critical minerals" for the energy transition:

- **Lithium, cobalt and nickel** for electric vehicle batteries and energy storage.
- **Copper** for a variety of clean energy technologies and, with **aluminum**, for electricity transmission and distribution infrastructure.
- **Manganese** used in lithium-ion batteries.[119]
- **Rare earth elements** (such as neodymium and dysprosium) for the magnets used in wind turbines and electric motors.
- **Graphite** for electric vehicle batteries and energy storage.[120]

Other minerals are important for specific technologies that may or may not have a significant role in the clean energy transition. **Platinum,** for example, is a key component of many hydrogen fuel cells and electrolyzers,[121] while metals such as **indium** and **gallium** are important for thin-film photovoltaics,[122] which have a small share of the overall solar photovoltaic (PV) market today but may become more prominent in the years to come.

In this report, we focus on five types of critical minerals: **copper**, **cobalt**, **lithium**, **nickel** and **rare earth elements** (specifically, neodymium and dysprosium). These are metals that are believed to be essential to the clean energy transition, face potential supply shortages, and are discussed as potential targets for deep-sea mining.

Demand for critical minerals is expected to grow, but forecasts vary widely

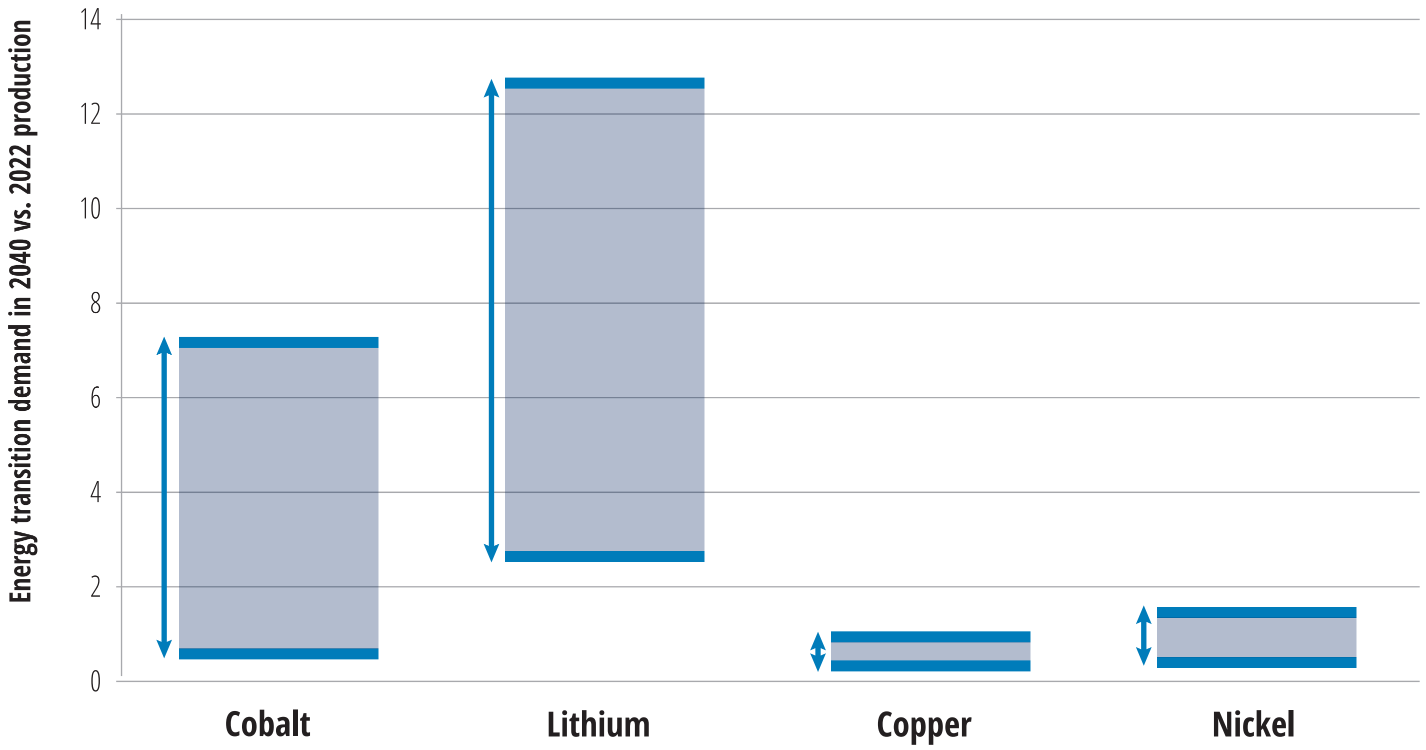
The widespread adoption of clean energy technologies will lead to significant – and, in some cases, dramatic – increases in the demand for some critical minerals. However, forecasts of the extent of that demand growth vary widely.

A 2023 meta-analysis by the International Energy Forum and the Payne Institute of Public Policy at the Colorado School of Mines illustrated the great variance in forecasts of future critical minerals demand:

- Forecasts of **cobalt** demand for energy transition technologies in 2040 varied from 58% to 725% of 2022 global demand, with the highest and lowest estimates differing by a factor of 12.5.
- **Lithium** demand forecasts for clean energy varied from 254% of 2022 demand to more than 1,000%, a factor of about four.
- **Copper** demand forecasts for 2040 varied from approximately 25% to 100% of 2022 demand, a factor of approximately four.
- **Nickel** demand forecasts varied from 33% of 2022 demand to 154%, nearly a factor of five.[123] (See Figure 2, next page.)

> *"[L]and-based resources are more than sufficient to meet cumulative future demand for critical raw materials from the energy transition – exploiting deep sea resources in [the] future would be a choice (with associated trade-offs), not an obligation."*
>
> **Energy Transitions Commission, July 2023[133]**

Figure 2. Range of forecasts for critical minerals demand[124]



Why do forecasts of critical mineral needs vary so greatly? In addition to the normal uncertainty present in any predictions of the future, two other key factors are:

- **Uncertainty about the future energy mix –** There are many potential paths to a zero-carbon energy system. For example, a transition more reliant on wind energy – and particularly offshore wind – could require greater supplies of rare earth elements compared with a transition that is more reliant on solar energy and battery storage, which may require greater supplies of metals like copper, cobalt and nickel.
- **Uncertainty about material needs of specific technologies –** In addition to the numerous pathways to a clean energy future, there are multiple variations of specific technologies such as batteries or solar panels, with significant implications for future materials demand. For example, until recently, most electric vehicle (EV) batteries required the use of large amounts of nickel and cobalt. Battery manufacturers have already taken steps to significantly reduce the amount of cobalt used in batteries,[125] and other battery designs now entering widespread use eliminate the need for both nickel and cobalt.[126] Still other emerging designs also eliminate the need for lithium.[127] The speed and extent to which these newer, less critical mineral-intensive technologies emerge is highly uncertain. Nevertheless, several major global automakers, including BMW, Volvo, Volkswagen, Renault and Rivian, support calls for a moratorium on deep-sea mining.[128]

Table 1. Anticipated energy transition demand for critical minerals, reserves and resources, world (metric tons)[131]

Mineral	Forecast annual energy transition demand, 2035	Reserves	Resources (identified)
Copper	15 million	1 billion	2.1 billion
Cobalt	265,000	11 million	25 million
Lithium	969,000	28 million	105 million
Nickel	1.69 million	>130 million	>350 million
Rare earth elements		110 million	
> Neodymium	61,000		
> Dysprosium	5,900		

Table 1 above shows the median forecast of annual energy transition critical minerals demand for 2035 from the International Energy Forum/Payne Institute literature review referenced above (with the exception of dysprosium, see endnote), compared with global reserves and resources of those minerals.[130]

In sum, demand for many critical minerals will increase in the years to come as the world shifts from relying on fossil fuels to harnessing our tremendous potential for renewable energy. *How much* the demand for specific critical minerals will increase depends on technological developments and market forces – as well as the degree to which economies can manage to limit the growth in demand for critical resources while continuing to advance the clean energy transition.

Deep-sea mining is a potential source of some, but not all, critical minerals

Some minerals – such as copper, nickel and cobalt – are potentially available in great abundance in seabed deposits. Others, such as lithium and rare earth elements, are also present in deep-sea mineral deposits, but in more limited concentrations or only in specific locations. Still other minerals critical to the energy transition are not available at all in the deep sea.

Even for some minerals that are present in large volumes in seabed deposits, such as manganese, copper

“Reserves,” “resources” and “materials in use”

Mineral **resources** are deposits that, according to the U.S. Geological Survey, exist “in such form and amount that economic extraction” of the mineral is “currently or potentially feasible.”

Reserves represent the share of mineral resources that “could be economically extracted or produced” at the current time.[132]

The amount of mineral reserves is always lower – and often significantly lower – than the amount of mineral resources.

Both reserves and resources refer to minerals that have not yet been extracted from the earth. As will be discussed in the following sections, there are large amounts of critical minerals embedded in the products and infrastructure we use every day, as well as in the waste we produce. “In-use” materials describe minerals that have already been extracted and are currently in use in the economy. These are materials that could conceivably serve as a future source of critical minerals when the products that include those minerals reach the end of their useful lives.

Table 2. Estimated mineral availability in selected deep-sea deposits vs. global reserves and resources (million metric tons)[135]

	Clarion-Clipperton Zone	Prime Crust Zone	World reserves	World resources
Cobalt	**44**	**50**	**11**	**25**
Copper	226	7	1,000	2,100
Lithium	3	0.02	28	105
Nickel	274	32	>130	>350
Rare earths	15	16	110	n/a

Bold: Volume available in deep-sea resource is greater than terrestrial resources.

and nickel, deep-sea mining is unlikely to be a critical source of material for the clean energy transition given the large existing demand for those minerals in other sectors of the economy.

Is deep-sea mining necessary for the clean energy transition?

The mere presence of critical minerals on the ocean floor – even in large volumes – does not mean that exploiting those deposits is necessary to advance the clean energy transition. For deep-sea mining to be essential, the resources available on the seafloor would need to be significant in the context of future global demand for those materials and production would need to be able to ramp up quickly enough to close global supply gaps that may emerge in the next decade, when options for expanding terrestrial mining or reducing critical minerals demand through technological advances or circular economy strategies are limited.

The only two metals for which deep-sea mining is capable of making a significant dent in the market are cobalt and nickel – two metals for which long-term demand is the most uncertain and "sufficient supply [is] expected to serve short-term demand" according to the International Energy Agency.[134]

Some critical minerals are available in only limited volumes on the seabed

Deep-sea mining is promoted as a solution to the critical minerals challenge, yet only some critical minerals are present in abundance on the seabed, while others are present only in more limited quantities, or in specific areas of the ocean.

Cobalt, copper and nickel supplies, as noted above, are present in abundance in seafloor nodule deposits in the CCZ and elsewhere. The European Academies Science Advisory Council anticipates that cobalt, copper and nickel, along with manganese, are likely to be the economic targets for mining of nodules and ferromanganese crusts, while copper, along with zinc, silver and gold, will be the economic targets of hydrothermal sulfide mining.[136]

> *"The argument that deep-sea mining is essential to meet the demands for critical materials is thus contested and does not support the urgency with which exploitation of deep-sea minerals is being pursued."*
>
> **European Academies Science Advisory Council[149]**

Other critical minerals, however, are available in only more limited volumes:

- **Lithium** can be present in seafloor crusts and nodules, but is not generally considered a target of deep-sea mining.[137] A study produced for the International Seabed Authority estimates that nodules in the CCZ possess less than one-fifth the amount of lithium as is present in current global land-based reserves.[138] According to an Environmental Justice Foundation report, "lithium is not currently targeted by the [deep-sea mining] industry and, at trace levels, is not viable for extraction from polymetallic nodules."[139] Norway estimates that lithium resources on the seafloor in its territorial waters equate to only about 1% of global land-based reserves.[140]

- **Rare earth elements** are present in varying amounts in various seabed environments. Nodules in the CCZ contain an amount of rare earth elements that is only a fraction of the world's land-based reserves.[141] Rare earths in the Prime Crust Zone in the central Pacific Ocean represent a similar share of global land-based reserves.[142] While concentrations of rare earth elements in seafloor deposits are low, some deposits are particularly rich in "heavy" rare earth elements (such as dysprosium) that are potentially of greater economic value.[143]

How important is energy as a share of overall mineral demand?

While the renewable energy transition will likely require significant quantities of manganese and copper, seabed mining is unlikely to have a significant impact on the global supply picture for copper and is not likely to be needed to satisfy manganese demand for the energy transition.

- **Copper –** Seabed mining is unlikely to have a major impact on the global supply of copper in the near- to mid-term. A study conducted for the International Seabed Authority estimates that, even with rapid deployment of deep-sea mining in the CCZ, it could only supply a maximum of the equivalent of 2% of current land-based production by 2035.[144]

- **Manganese –** Similarly, while the energy transition will likely require an increase in manganese use,[145] existing and planned land-based resources are forecast to meet demand in the near-term in all but the highest demand cases.[146] Other uses, not energy transition uses, would likely drive any deep-sea mining for manganese. For example, The Metals Company, which has proposed to begin mining for nodules in the CCZ, has indicated that it wants the manganese for steel production.[147]

While deep-sea mining does have the potential to produce copper and especially manganese, it will not produce enough of the former to make a dent in global markets, and the latter is not likely to be in especially short supply. Moreover, the widespread use of copper and manganese throughout the economy provides an abundance of opportunities to manage potential increases in demand resulting from the energy transition.

In sum, from the perspective of the clean energy transition, **nickel** and **cobalt** are the metals that are likely to be economic targets of deep-sea mining, but are not at great risk of short-term supply disruption; and new nickel- and cobalt-free EV battery designs are rapidly gaining market share, potentially reducing the importance of those metals for the energy transition. **Rare earth elements** and **lithium**, while extremely important to the clean energy transition, are unlikely to be produced in great abundance from seafloor mining. **Copper** and **manganese** may be economic targets for deep-sea mining, but deep-sea extraction of those metals is not likely to be essential to meet the needs of the energy transition.

Can deep-sea mining address near-term shortages of critical minerals?

The absolute quantity of critical minerals available from land-based resources is unlikely to be a constraint on the clean energy transition, at least through 2050.[148] The major challenges are bringing enough critical minerals to market fast enough to support the dramatic ramp-up in clean energy proposed by many of the world's nations to accelerate the transition away from

> *"The remarkable success of these [new] EV batteries and many other new chemistries coming to market, along with growing battery-recycling solutions, has eliminated the claimed need for deep-sea mining to support the growing EV market."*
>
> **Dr. Daniel Kammen, University of California, Berkeley, February 2024**[129]

fossil fuels, while limiting environmental impacts from any expansion of terrestrial mining.

The period between now and 2035 is most critical. Copper and nickel mines require at least seven to eight years, and sometimes much longer to come online, while lithium mines can take at least four to seven years to develop.[150] Technological changes that could dramatically reduce demand for certain critical minerals – such as changes in EV battery chemistries – take at least several years to roll out. While some circular economy strategies – such as product lifetime extension and repair – can make an immediate difference, others, such as recycling, require time to ramp up and are only capable of making a limited difference in the short run as the first generation of EV batteries and solar panels are now beginning to reach the end of their useful lives.

Analysis produced for the International Seabed Authority and published in 2022 concluded that cobalt and nickel were likely to experience supply shortages toward the end of the 2020s, and in both cases, a rapid ramp-up of nodule harvesting from the deep sea could meaningfully reduce those shortages.[151] More recent analysis, however, suggests that neither cobalt nor nickel are likely to be at risk for short-term supply disruption.[152] Other observers question the ability of deep-sea mining to make a meaningful contribution to short-term supply challenges. The Energy Transitions Commission concluded in 2023 that "initial production amounts [from deep-sea mining] are likely to be low and not able to significantly close supply gaps that might emerge by the late 2020s."[153] The assumption that deep-sea mining can come online quickly enough to address any shortages is open to question.

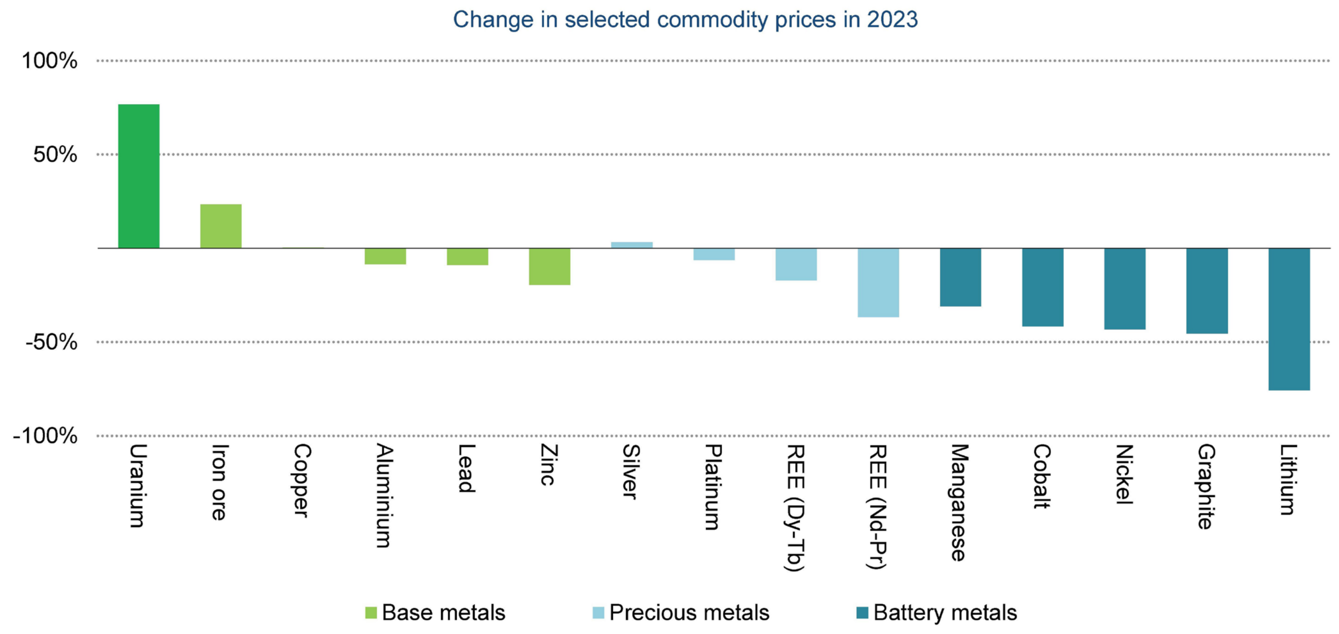
The report produced for the ISA, and cited earlier, bases its conclusions on the assumption that seabed mining production would begin in 2027. However, there is no guarantee that seabed mining can or will scale up that quickly. The Metals Company, which hopes to receive permission to mine nodules in the CCZ, has stated that "we expect to be in production in the fourth quarter of 2025 if the application [to the ISA] is approved."[154] While, as of early 2024, the ISA was targeting 2025 for the adoption of regulations on seabed mining, some analysts argue that the number of outstanding regulatory issues to be resolved makes such a timeline unrealistic.[155]

Meanwhile, markets for several critical minerals – including nickel and cobalt – were no longer showing signs of shortage as of mid-2024, instead surging into surplus, sending prices for those materials tumbling.

During 2023 alone, cobalt prices fell by an estimated 25%, nickel prices by 45% and lithium carbonate prices by 70%.[157] Nickel production has increased,[158] leading some analysts to forecast a surplus of nickel through at least 2028.[159] Nickel producers have also expanded their capacity to process low-grade nickel ore typically used in stainless steel to the higher-purity metal required for EV batteries, adding additional flexibility to nickel supplies.[160]

Cobalt markets – which experienced greater demand than supply as recently as 2021 – have turned to

Figure 3. **Price trends during 2023 for energy transition minerals (source: International Energy Agency)**[156]



IEA. CC BY 4.0.

Notes: REE = rare earth elements; Dy-Tb = dysprosium and terbium; Nd-Pr = neodymium and praseodymium. Change in prices between December 2022 and December 2023.
Sources: IEA analysis based on Bloomberg and S&P Global.

surplus, with newer battery designs reducing demand for the metal at the same time that new cobalt supplies have come online.[161] Like nickel, cobalt is anticipated to remain in surplus through at least 2028 amid increases in production and an increase in the use of cobalt-free batteries in China.[162]

Rare earth element prices also plunged in 2023 amid rising supply and slow demand, though supply cuts by China, by far the world's leading producer of rare earth elements, could cause prices to rebound later in 2024.[163]

The falling prices for some critical minerals – as well as the price volatility in metals markets and the unknown costs of producing metals in harsh ocean environments at large scale – raise questions about the economic viability of deep-sea mining. The Metals Company saw its stock price decline by more than 90% between late 2021 and mid-2023, before experiencing a modest rebound.[164] The analysis conducted for the ISA and cited above notes that, because seafloor nodules consist largely of four metals (nickel, cobalt, copper and manganese), "[a] decrease in the price of one or more of the four metals by any cause (including the very beginning of deep-sea mining) automatically reduces the market value of the polymetallic nodules as raw materials for these metals. Such a decline may result in some or even all of the deep-sea mining projects becoming subeconomic or unprofitable."[165]

All of this suggests that while deep-sea mining *could be* one of the strategies used to meet the anticipated midterm surge in demand for critical minerals, the world cannot and should not rely on it – especially when, as described in the sections that follow, ample opportunity exists to reduce our demand for critical minerals and encourage repair, recycling and reuse. Uncertainty around the speed, scale, regulatory treatment, and technical and economic viability of deep-sea mining, coupled with near-term surpluses of several critical minerals, means that building the energy transition around deep-sea mining is not a wise idea – even without considering the devastating and irreparable harms it would likely inflict on ocean ecosystems.

> *"It is unlikely that terrestrial mining would be displaced significantly if deep-sea mining were to commence; the sectors would become competitors in a larger minerals market without a transformational economy that reduces demand."*
>
> **Miller, et al., *Frontiers in Marine Science*, July 2021[166]**

Would deep-sea mining alleviate the need for land-based mineral extraction?

One potential justification for deep-sea mining is that, while ocean-based extraction of critical minerals poses ecological risks, those risks are lower than those posed by terrestrial mining. As discussed above, such a comparison is impossible to make without a fuller understanding of the dangers that seafloor mining is likely to impose, and it is entirely possible that the ecological impacts of seafloor mining may rival or exceed those of land-based mining.

Commencement of deep-sea mining, however, would not necessarily lead to the elimination of, or even a significant reduction in, terrestrial mining. [167] If deep-sea mining were to produce minerals significantly cheaper than land-based mines, some terrestrial mining could be displaced. However, the reduction in price would *also* erode the economic viability of deep-sea mining itself and undermine incentives for manufacturers of clean energy technologies to adopt less metals-intensive designs, as well as incentives for societies to adopt strategies that can reduce demand for critical minerals. (See next chapter.) As the recent shift away from cobalt in EV batteries – and the increasing adoption of cobalt- and nickel-free batteries – shows, concerns about mineral price and availability can drive technological innovation and do so rapidly.

The most effective ways to reduce the environmental and other impacts of land-based mining are to support greater regulation, supply-chain monitoring and accountability for the mining industry around the world and reduce the need for newly mined materials to begin with through a more sustainable approach to product design, use, repair and end-of-life reuse and recycling.[168] Opening up new areas of the planet for new forms of damaging mineral exploitation is not an effective strategy to reduce the harms of existing methods of mining.

> *"This is a rush to mine minerals that may not be that necessary in the next even five years when the environmental damage could be not only extensive but permanent."*
>
> **Victor Vescovo, Founder, Chief Executive, and Chief Submersible Pilot at Caladan Oceanic and Co-Founder of Insight Equity[169]**

Building a “circular economy” for critical minerals with the “5 Rs”

We do not need to mine the bottom of the ocean for the minerals needed to power the energy transition. Many of the resources the world needs to transition to renewable energy are already in our hands. And, by designing the new clean energy economy around products that are built to last, fixable when they break, and reused or recycled at the end of their useful lives, we can dramatically reduce the amount of critical minerals we need to extract at all.

A circular economy, according to the U.S. Environmental Protection Agency, “reduces material use, redesigns materials and products to be less resource intensive, and recaptures ‘waste’ as a resource to manufacture new materials and products.”[170] Circular economies are nothing new – humans have a long history of building things to last and using the “waste” from one activity as a resource for another. Circular economy approaches do, however, stand in stark contrast to the modern, one-way “take-make-waste” linear materials economy that has become increasingly common around the world – one in which materials are extracted from the earth, used in products for a brief period of time, and then returned to the environment as waste.

Building a circular economy for critical minerals in the energy transition begins with following the “5 Rs” – the traditional “3 Rs” of **reduce, reuse, recycle**, plus two other steps: **reimagining** products to make more efficient use of materials and be built to last, and **repairing** products to further extend their lifespans.

Figure 4. Circular economy strategies for clean energy minerals

REDUCE

Energy efficiency/conservation

Systems efficiency

REIMAGINE

“Designed to last” products

Material substitution

Limiting disposable electronics

REUSE

Second-life applications

RECYCLE

End-of-life product recycling

“Urban mining”

Material recovery from industrial/mining waste

REPAIR

Design for repairability

Right to repair

Numerous studies have identified the potential for circular economy approaches to reduce demand for critical minerals – both immediately and over time:

- A 2022 study conducted for the World Wide Fund for Nature (WWF) found that a series of circular economy strategies (including reduced demand and product lifetime extension) could reduce cumulative demand for energy transition minerals between 2022 and 2030 by 18%.[171] A combination of technological change, recycling and other circular economy strategies, the study found, could reduce cumulative demand for critical minerals by 58% through 2050. [172]
- A similar set of product redesign and circular economy approaches are estimated by the Energy Transitions Commission to be able to fully close projected supply gaps for copper and nickel, and significantly narrow them for lithium, cobalt and neodymium by 2030.[173]
- The International Energy Agency estimates that a combination of technology change, recycling and reduced EV battery sizes could reduce demand for lithium by 25% in 2030 in a scenario that reaches net zero greenhouse gas emissions by 2050. Smaller batteries and technological changes can also reduce demand for nickel and cobalt by 2030.[174]
- In the longer run, a 2021 study by researchers from Japan and Australia found that circular economy approaches could reduce the need for resource extraction for the electricity sector by 23% by 2050 and for the transportation sector by 60% in a scenario that limits global warming to below the 2° Celsius goal of the Paris Climate Agreement.[175]

There are many opportunities to reduce the mineral needs of the energy transition through the “5 Rs.”

Reduce

Many of the ways the world uses energy are not just carbon-intensive, they are also wasteful. Eliminating energy waste – through systems-level change and changes in the marketplace and consumer behavior – can reduce the number of wind turbines, solar panels and batteries needed to decarbonize the economy, and the resulting consumption of raw materials. Specific tools that can help to reduce demand for energy and for minerals-intensive equipment include:

- **Improving end-use energy efficiency:** Weatherization of homes and commercial buildings, adoption of energy-efficient appliances, and design changes that reduce vehicle energy consumption can all meaningfully reduce demand for energy. Recently announced energy efficiency standards for residential clothes washers and dryers in the U.S., for example, will save an estimated 3.4 quadrillion Btu of energy over 30 years of shipments, equivalent to nearly 4% of the energy the United States consumes in a single year.[176]
- **Matching electricity demand to supply:** Better aligning electricity consumption with production from wind, solar and other forms of renewable energy can reduce the amount of transmission infrastructure and energy storage required to maintain balance on the grid. A 2021 study estimates that combining energy efficiency and demand flexibility in U.S. buildings could save up to 800 terawatt-hours of electricity annually and reduce daily net peak load by more than 200 gigawatts (GW) by 2050.[177] The electricity savings is equivalent to about one-fifth of current U.S. electricity consumption,[178] and the peak load reduction is equivalent to more than 10 times the amount of battery energy storage currently installed on the U.S. grid.[179] In addition, the study finds that a significant share of those reductions could be achieved by 2030, allowing the United States to decarbonize faster while reducing the strain on critical minerals.
- **Getting more from our batteries:** Energy storage will be a critical resource to help the nation transition from dirty to clean sources of energy. With the adoption of vehicle-to-grid or vehicle-to-building technologies, materials used in electric vehicle batteries could do double duty as sources of energy storage for households or the grid. A 2023 study estimates that EV batteries globally –

including both those that have been retired from use in vehicles but repurposed for grid storage and those that remain in use in vehicles and could supply storage through vehicle-to-grid connections – could meet all of the need for short-term energy storage by 2030,[180] reducing the amount of minerals needed to build batteries specifically for grid-scale energy storage.

- **Improving systems efficiency:** America's transportation system is energy-intensive, with people driving long distances daily in large, inefficient, individually owned vehicles. A 2023 report by the Climate and Community Project found that reducing car dependency and using smaller batteries could reduce demand for lithium for electric vehicle batteries by between 18% and 66% compared with a reference scenario.[181] Systems-level changes – including increasing access to public transit and active transportation modes such as walking and biking – can help to realize these savings.

- **Managing new sources of demand growth:** Electrification of buildings and transportation are anticipated to lead to an increase in demand for electricity in future years. But, recently, an array of other potential sources of demand – from cryptocurrency and artificial intelligence to electric vehicle factories and hydrogen production facilities – have begun to pose serious concerns about strain on the grid.[182] Accommodating these sources of demand would require a bigger build-out of the nation's clean energy infrastructure and, with it, additional demand for critical minerals. It is imperative that, as the clean energy transition gets underway, there is caution about adding new sources of demand, some of which may be of limited societal value.

- **Greater efficiency in use of materials:** Getting more and better performance out of less material-intensive clean energy technologies is another way to reduce the growth in materials demand for the energy transition. Technological improvements have tripled the amount of energy that can be stored in lithium-ion battery cells per unit of weight since 2010, allowing our vehicles to travel longer distances without increasing demand for materials.[183] There remains, however, significant room for additional improvement, including improving the efficiency of the battery manufacturing process to reduce waste.[184]

The United States and the world face critical choices in designing energy systems for a carbon-constrained world. One possible path would give little thought to efficiency or managing demand. That path would require a potentially endless cycle of construction of new power generators and electricity lines, straining the planet's resources and opening the door for destructive modes of extraction such as deep-sea mining. The other would moderate growth in energy demand, including through "win-win" strategies such as energy efficiency, while maximizing the amount of constructive use we get from every bit of raw material we extract from the earth. This latter path would significantly reduce demand for energy transition metals.

Reuse

Energy technologies, like all products, have a finite useful life. Ensuring that those products maximize their useful lives by creating vibrant markets for used and refurbished electric vehicles, solar panels and other equipment can ensure that the minerals extracted for their construction deliver the greatest possible benefit.

Even after some clean energy technologies reach the end of their useful lives for the purpose for which they were originally designed, they may still be useful for other purposes. EV batteries that are no longer capable of powering a car, for example, can still contribute to the energy transition by serving a "second life" as electricity storage for the grid, either reducing the need for newly built batteries or helping to accelerate the addition of more clean energy to the grid. (See "Second-life EV batteries," page 38.)

Recycle

Recycling is perhaps the most obvious strategy for reducing demand for extraction of new minerals. While recycling is a potentially powerful tool to address long-range mineral supply challenges, it has limitations as a solution in the short run.

In this section, we classify under the banner of "recycling" three approaches for recovering materials from waste: traditional end-of-life recycling programs, "urban mining" of e-wastes and landfills, and recovery of waste products from industrial processes.

Recycling of end-of-life products

Several critical minerals are already widely recycled, while, for others, recycling is only in its infancy. Nevertheless, analysts suggest that recycling can play an important role in building a circular economy for critical minerals – especially in the years to come as the first generations of clean energy technologies come to the end of their useful lives.

Some metals essential to the energy transition, including lithium and rare earth metals used in permanent magnets, are barely recycled at all in the United States or globally.[185] Other metals, such as copper, nickel and cobalt are already widely recycled, with end-of-life recycling rates ranging from 40% to nearly 70%.[186]

Tremendous potential exists to increase recovery and recycling of both categories of metals. For example, an estimated 950,000 metric tons of copper in cables was discarded globally in 2022.[187] With improved collection, recycling rates of up to 70% for lithium, 90% for cobalt and 70% to 90% for rare earth elements may be possible.[188]

Continued improvements in the collection of materials for recycling and their conversion into usable feedstocks could significantly ease near-term demand for critical minerals. A study produced by the Institute for Sustainable Futures at the University of Technology Sydney (UTS) for Earthworks estimates that, by 2030, improved metals collection and recycling could supply enough cobalt for 1 million EV batteries, enough lithium for 5.5 million batteries, enough nickel for 1.5 million batteries and enough copper for 5.5 million batteries.[189] Even greater levels of replacement could be achieved by 2040 or 2050.

Meeting those targets would require big but technologically feasible improvements in systems to collect and process recyclable material. For example, despite the surge in the use of lithium-ion batteries in consumer electronics, only about 5% of lithium batteries in the United States are currently recycled.[190] Globally, the end-of-life recycling rate for lithium is less than 1%.[191] Expanded lithium recycling is possible; however, the wide variety of lithium battery designs in consumer products, among other factors, have made recycling of lithium-ion batteries difficult to date.[192]

The infrastructure for widespread recycling of lithium-ion EV batteries is beginning to come online, following a massive surge in venture capital investment in battery and waste recycling in 2022 and 2023.[193] Redwood Materials, for example, now recycles EV batteries at its Nevada facility, reclaiming 95% of the lithium in spent batteries, as well as cobalt and nickel, using a process that it claims delivers dramatic reductions in carbon dioxide emissions relative to mined materials.[194] The company is currently building a second facility in South Carolina and has signed agreements with major automakers and battery manufacturers. The firm hopes to produce enough anode and cathode materials to power 1 million EVs annually by 2025 and 5 million per year by 2030.[195]

In the case of rare earth metals, recycling is at an even earlier stage, with significant technical challenges. But the potential to avert the need for new supplies is great. One recent study estimated that reused or recycled rare earths could satisfy 40% of demand in the U.S., Europe and China by 2050.[196] Other analysts are even more optimistic, estimating that recycling could meet as much as half of all demand for dysprosium and 80% of demand for the rare earth metal neodymium by 2050.[197]

“Urban mining”

“Urban mining” has been defined as “the process of recovering raw materials – mostly metals and minerals – from e-waste largely found in cities.”[198] It includes both recovery of materials from electronic wastes stored in desk drawers, basements and office tech closets and the literal “mining” of landfills and other disposal sites for minerals in discarded e-wastes and other products. In some cases, “urban mines” contain concentrations of critical minerals that are comparable to or higher than those found in virgin ore.[199] Even where concentrations of critical minerals are low, the presence in landfilled e-waste of other valuable minerals such as gold and silver may help to make extraction economically viable.[200]

Minerals from industrial waste

There is also potential to extract valuable materials from industrial waste streams – including some that have been notorious sources of environmental pollution.

Coal ash – the waste product from coal combustion – is often stored in pits adjacent to electric power plants across the country. A highly toxic waste product, spills of coal ash have devastated waterways and put human health at risk.[201] That waste, however, is also a potentially important source of critical minerals. Coal ash in the U.S. may contain as much as 172,000 tons of the rare earth metal neodymium, equal to more than two years’ worth of global supply at 2022 levels, as well as large amounts of dysprosium, nickel and cobalt.[202] Slag from the steel production process, petroleum wastes, and wastes from the aluminum production process are other potential sources of critical minerals.[203]

Extracting minerals from industrial and mining wastes must be done with care, both to avoid creating additional environmental harms and to avoid creating economic incentives for the continuation of unsustainable modes of resource extraction.

Reimagine

One way to use fewer critical minerals is to innovate our way to needing less of them. Rising prices or the threat of imminent shortages of specific materials often drive scientists, engineers and companies to investigate ways to reduce the use of those materials in products or eliminate them entirely. Material substitution has occurred over and over again in the transition to clean energy – in recent years, for example, battery manufacturers have dramatically reduced their use of cobalt in favor of nickel in lithium-ion batteries. Innovation can also enable us to build products that need to be replaced less frequently, reducing the “churn” of critical minerals through the economy.

Potential opportunities for material substitution exist across a range of clean energy technologies:

- **Electric vehicles:** Emerging battery designs could dramatically reduce demand for cobalt, nickel and, eventually, lithium. Lithium iron phosphate (LFP) batteries avoid the use of nickel and cobalt and accounted for 27% of world’s light-duty EV battery sales in 2022, up from 3% in 2019, with Chinese manufacturers leading the way.[204] Tesla began including LFP batteries in some of its U.S. vehicles in 2022.[205] Technological substitution in batteries could reduce cumulative demand for nickel by about 12% and cumulative demand for cobalt by 19% over the period from 2022 to 2050.[206] One analysis estimates that the adoption of cobalt-free batteries would allow annual cobalt demand for electric passenger vehicles to peak by 2038 and fall to 1% to 2% of its peak level by 2050.[207]

- **Wind turbines:** Numerous options exist to reduce or eliminate the use of rare earth elements in wind turbines. The vast majority of onshore wind turbines in the U.S. use designs that are relatively light in rare earth elements, though turbines with rare earth-containing permanent magnets are often favored for offshore turbines due to their efficiency and reduced need for maintenance. [208] Researchers are currently working to develop permanent magnets that reduce or eliminate the need for rare earth elements.[209]

- **Electricity infrastructure:** Aluminum can substitute for copper in many applications, both in consumer products and in the transmission lines and distribution wires used to carry clean electricity from where it is generated to where it is used. Aluminum has about 60% of the electrical conductivity of copper, but is lighter, cheaper and more abundant.[210]
- **Energy storage:** Lithium-ion batteries have been the primary battery technology used in U.S. grid-connected energy storage systems to date, but there are a wide variety of other battery types – and other, non-battery forms of energy storage – that could either substitute for lithium-ion batteries or fill other roles in providing necessary energy storage for the grid. [211] Sodium-ion batteries, whose low energy density has thus far made them challenging to integrate into EVs, are a potential candidate for grid-scale storage, reducing the demand for lithium (though not necessarily for other critical minerals.)[212] Flow batteries and zinc-based batteries are other alternatives,[213] while thermal and mechanical forms of energy storage are likely to be more attractive alternatives for storing energy for longer periods of time.[214]

Material substitution is not a panacea – it can result in simply shifting shortages or the environmental impacts of production from one place to another. It can also be accompanied by trade-offs in performance. Material substitution remains, however, a powerful strategy to avoid shortages of specific minerals or to adapt to limits on resource extraction imposed by the need to protect vulnerable ecosystems and human health.

Reimagining the products we use to enable them to last longer – and using the 5th "R" of repairing them when they break – are additional ways to "get more from less," and reduce the impact of any potential near-term shortages in critical minerals.

Extending product lifetimes: A key solution to the critical minerals challenge

An important, and often forgotten, source of critical minerals exists all around us – in the products we own, the homes in which we live, and the infrastructure that connects us. One simple and powerful solution to the critical minerals challenge is to get more out of the products we already own.

Extending the lifetimes of products already in the economy can help to alleviate pressure for new extraction as the energy transition gains momentum. And reimagining products so that they are built to last, and able to be repaired when they break, can help to lay the foundation for a circular economy in critical minerals, with greatly reduced need for extraction of new materials from the earth for decades to come.

Extending product lifetimes can come with tradeoffs, especially when it comes to rapidly advancing clean energy technologies. Many clean energy technologies, however, can still be reused in less-demanding "second life" applications.

The critical minerals all around us

Many critical minerals have been in widespread use in the economy for generations. As a result, the critical minerals in the buildings, infrastructure and products we have already made are a potentially important resource that can be used to bridge the gap to a sustainable clean energy economy.

The amount of critical minerals already in use in the world's economy rivals, in some cases, the amount that exists in yet-to-be-mined reserves. As of 2020, for example, there were 470 million metric tons of copper in use worldwide.[215] That is about 47% of the 1 billion metric tons of copper reserves around the world.[216] It is also about 31 years' worth of energy transition demand at anticipated 2035 demand levels.[217] (See Table 3.)

Other critical minerals are also used in a variety of products. As of the late 2010s (that is, early in the global transition to electric vehicles) about half of all cobalt was used in ceramics and glass, and

Table 3. Amount of material currently in-use vs. global reserves and resources[218]

Mineral	Metric tons in use	Reserves	Resources (identified)
Copper	470 million	1 billion	2.1 billion
Cobalt	471,000	11 million	25 million
Nickel	29 million	>130 million	>350 million

in lubricants and greases, continuous casting and polymer production.[219] Permanent magnets containing neodymium are in widespread use in industrial motors; automobile motors (including small motors such as those in automatic windows); air-conditioning compressors; electric bicycles and scooters; DVDs; and magnetic resonance imaging machines.[220] Dysprosium follows similar patterns of demand, with industrial motors the largest single demand category as of 2015. [221]

The widespread use of critical minerals throughout the economy means that efforts to extend the lifespans of a wide variety of consumer products – including, but not limited to products essential for the energy transition – can help to smooth out the rapid increase in demand anticipated in the next 10 to 15 years. It also illustrates the potential benefits of establishing effective reuse and recycling programs for *all* products in our economy.

Critical minerals in products and e-waste are an abundant domestic resource

The production of some critical minerals is currently highly concentrated in a few countries around the world, leading to concerns that minerals may become unavailable in the event of a breakdown in trade relationships or international conflict. China's dominance in the mining and processing of rare earth metals – and its willingness to restrict exports of rare earths and related technologies – is one example of the dynamics that have led nations to focus increasingly on securing supplies of critical minerals from domestic resources or allies.[222]

America's capacity to produce critical minerals varies, but the United States is unusually well-situated to make use of critical minerals in existing products and electronic waste – providing a golden opportunity to reduce our dependence on other nations.

The United States generated more e-waste in 2022 than any other country in the world, a total of 7.2 million metric tons, or roughly 47 pounds per capita. While most of that waste (4 million metric tons) was "documented to be collected and recycled," according to the 2024 *Global e-Waste Monitor* report, that still leaves as much as 3 million metric tons of e-waste rich in critical minerals sent to landfills or incinerators.[223]

Unlike mines for critical minerals overseas, much of the critical minerals currently in use worldwide are located right here in the United States. There is approximately 350 pounds of copper currently in use in the U.S. economy for every man, woman and child in the country, as well as more than 30 pounds of nickel.[224] Avoiding the need to replace that material – and recovering and recycling it when it reaches the end of its useful life – can reduce demand for new mining.

Circular economy strategies are capable of eventually providing a steady stream of domestically available material even for those materials with limited natural deposits in the United States, such as rare earth elements. A 2024 study estimates that employing a variety of circular economy strategies (reduction in material use, substitution, reuse and recycling) could enable the United States to eliminate the need for imports of rare earth elements by 2050.[225]

The International Energy Agency recognizes that recycling is a valuable strategy to improve the security and sustainability of critical minerals supply.[226] Amid the current concerns about continued access to reliable supplies of critical minerals, the United States should take full advantage of the abundant resources available in products and equipment that have reached the end of their useful lives.

Reimagining and repairing products can reduce strain on critical mineral supplies

The circular economy strategies discussed in the previous section are important tools to reduce the material needs of the energy transition in the long run. But, as noted above (p. 22), perhaps the greatest concern relates to the potential short-term demand crunch for critical minerals as the world makes the rapid transition to renewable energy. While recycling, material substitution and energy efficiency improvements can make a big difference in the medium- to long-run, implementing them takes time.

Product lifetime extension can make an important and immediate impact on critical mineral demand. Assuming that product designs remain the same, increasing the lifespan of a device by 50% could reduce minerals demand for that type of device by as much as a third. Doubling the lifespan could reduce mineral demand by as much as half.

There are many opportunities to extend the lifespans of products currently in use in our economy. Consumer electronics – from smartphones to laptops – contain many of the same critical minerals as clean energy technologies, and because they are often used for only a short period of time, extending their lifespans can make an immediate difference.

And while there are relatively few solar panels, electric vehicles or wind turbines currently reaching the end of their useful lives in the United States, the numbers will grow significantly in the years to come. Extending the lifetimes of those technologies – including through "second-life" applications – can make a modest difference in demand for critical minerals in the short run and a much greater difference as time goes on.

Consumer electronics

Consumer electronics have driven the rise in demand for a variety of critical minerals over the last several decades. The most obvious drivers of that increase in demand have been smartphones – which have become nearly ubiquitous worldwide since their introduction in 2007 – and computers. But the past decade has also seen an explosion in small electronic devices, such as earbuds, e-cigarettes (or "vapes"), digital watches, fitness trackers, tablet computers, virtual reality headsets and more. The sheer number of these small electronics that are discarded annually is jaw-dropping – for example, more than 7 billion electronic toys were discarded worldwide in 2022.[227] Meanwhile, "smart" features have increasingly been integrated into common household appliances, turning virtually everything into a computer.

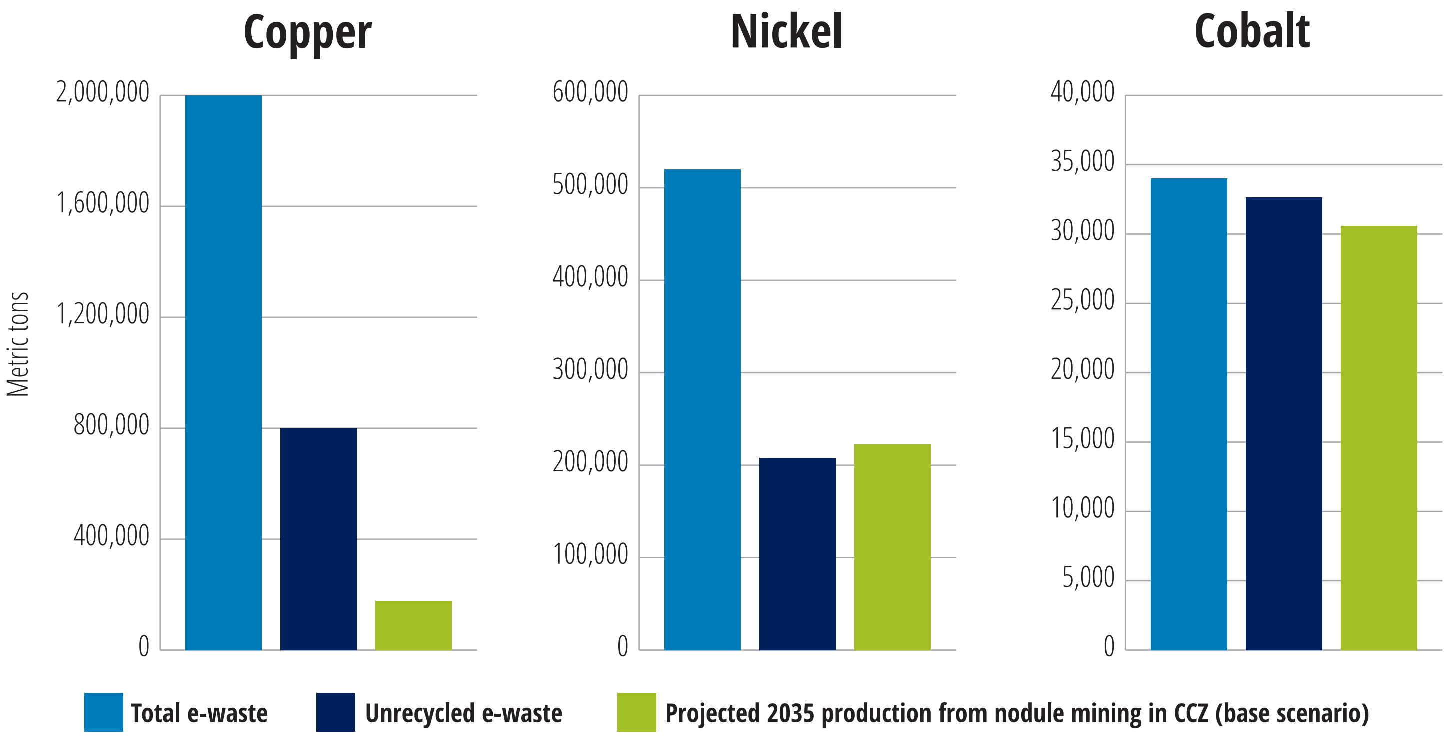
The result of this proliferation of short-lived electronic products is e-waste – the 2024 *Global E-waste Monitor* report from the United Nations estimates that 62 million metric tons of e-waste were generated worldwide in 2022 – equivalent to 17 pounds per person globally and 46 pounds per capita in the United States.[228] Only about 22% of the world's e-waste was properly recycled.

Reducing the amount of e-waste headed to landfills and incinerators – by extending product lifetimes, improving recycling or both – could eliminate the need for additional resource extraction from the seafloor and other sensitive areas. **In fact, the world currently trashes more copper and cobalt in discarded e-waste each year than would likely be produced annually by nodule mining in the Clarion-Clipperton Zone of the central Pacific Ocean through at least 2035.**[229] The amount of nickel in unrecycled e-waste represents more than 90% of what is expected to be produced annually from the CCZ in 2035.

The technical challenges of recycling e-waste, while not insurmountable, make extending the lifetimes of electronic products a compelling option for reducing critical mineral demand in the short run. Many consumer electronic products have short average lifespans – ranging from a couple of years in the case of a set of AirPods or a smartphone to a few days in the case of a disposable "vape." According to one study, the short average lifetimes of consumer electronics provide the opportunity for measures to improve resource efficiency to provide "quick results."[231]

The following are several examples – among thousands of possibilities – that illustrate the potential for extending the lifetimes of consumer products to alleviate demand for critical minerals.

Figure 5. **Annual e-waste production vs. projected annual production from nodule mining in Clarion-Clipperton Zone in 2035 (base scenario)**[230]



Smartphones

Smartphones are rich in critical minerals. A typical smartphone has approximately 6.6 grams of copper and 0.3 grams of rare earth elements, along with other important minerals.[232] Those numbers sound small, but with nearly 1.2 billion smartphones shipped worldwide in 2023, they quickly add up – equating to about 7,920 metric tons of copper and 360 metric tons of rare earth elements per year.[233]

Frequent product changes in the smartphone market – coupled with the designed-in difficulty of repairing some models – result in smartphones having extremely short lifespans, less than three years.[234] The vast majority of smartphones are not recycled at the end of their useful lives – in California, for example, only about 27% of smartphones are recycled.[235]

Extending the average lifespan of smartphones from 3 to 4.5 years could reduce demand for copper by up to 2,640 metric tons per year and demand for rare earth elements by up to 120 metric tons per year.

Headphones and earbuds

About 5% of all neodymium and dysprosium used globally in 2015 – nearly 1,400 metric tons of neodymium and nearly 165 metric tons of dysprosium – was for acoustic transducers, which convert electrical energy into sound in speakers, headphones and earbuds.[236]

This figure may be even higher today. These statistics date from before the introduction of Apple AirPods, the extraordinarily popular wireless earbuds. About three-quarters of a billion sets of wireless earbuds were sold between 2017 and early 2022.[237] Given the rate of growth in headphone sales worldwide, we estimate that roughly 150 metric tons of neodymium were used in headphones sold worldwide in 2022.[238]

AirPods and other earbuds, however, tend to have short lifespans – typically about two to three years[239] – are easily lost and are all but irreparable, meaning that the rare earth minerals within them often find their way into landfills. Apple's AirPods Pro received a 0/10 repairability score from iFixit.[240]

Apple now claims to use 100% recycled rare earth magnets in its second-generation AirPods,[241] removing one source of competing demand for rare earth elements. A more effective step (which would also potentially free up recycled neodymium for other uses) would be to design AirPods to last and allow them to be more easily repaired at the end of their useful lives. Extending the life of consumer headphones by 50% – for example, from two years to three years – could cut neodymium demand by as much as one third, or a maximum of 50 metric tons per year.

Vapes

Vapes are another small product with a big environmental impact. Vapes (or e-cigarettes) use critical minerals including lithium and copper.[242] While all vapes are potential sources of e-waste, recent years have seen a trend toward single-use disposable vapes – magnifying the resource consumption and pollution associated with vape use. Vapes produced globally in 2022 included roughly 130 metric tons of lithium, along with 1,160 metric tons of copper.[243] There is currently no standardized way to recycle vapes in the United States, meaning that all this material is eventually destined to wind up as waste.[244]

In the United States, disposable vape sales have been rising dramatically, accounting for roughly half the vape market in 2022.[245] Eliminating disposable vapes in favor of reusable vapes, and extending the lifespan of reusable vapes could be assumed to reduce metals demand for vapes dramatically.

Laptops

A 2011 analysis found that a typical notebook computer used 0.99 grams of nickel, 20 milligrams of neodymium and 270 grams of copper.[246] The poor state of electronics recycling means that many of those metals find their way into landfills when laptops reach the end of their useful lives … or remain stored in desk drawers, closets and basements along with other household and business e-wastes.

Extending the useful lives of laptops can reduce demand for critical minerals in new computers. A 2019 study examined the environmental benefits delivered by a Swedish service that refurbishes and resells second-hand laptops, effectively doubling the lifespan of the laptops from three years to six.[247] The analysis found a consistent reduction of metal consumption of 41% due to the extension of the product lifespan.[248]

Often, laptops in perfectly good working condition are rendered inoperable when manufacturers end support for operating systems or other critical software. In one European survey, roughly 1 out of 5 people who replaced a digital device reported that they did so because software stopped working.[249] Microsoft, for example, had planned to end security updates for computers using the Windows 10 operating system – a change that could have rendered as many as 400 million computers obsolete. The company eventually agreed to continue security support following an outcry from users and consumer advocates.[250] Similarly, Google agreed to extend support for its Chromebook computers – commonly used in schools across the country – due to concerns about e-waste among schools, parents and citizens.[251] A 2023 U.S. PIRG Education Fund report highlighted Google's practice of setting end dates for software support of Chromebooks that may not correspond to the ability of the machines to continue to function, leading some machines to be disposed of before the end of their useful lives.[252]

Globally, roughly 186 million notebook computers were produced in 2022.[253] Assuming a 41% reduction in metals use for a doubling of the product lifetime, and laptop composition similar to that estimated in the 2011 study, lifetime extension could save 75 tons of nickel and 20,590 tons of copper, along with a small amount of neodymium, annually.

Energy transition technologies

The first generation of solar panels, wind turbines and electric vehicle batteries are beginning to reach the end of what had been expected to be their useful lives. Extending their lifetimes can deliver many benefits by reducing demand for new, mineral-intensive technologies, accelerating the clean energy transition, or both.

Even more important than extending the lifetime of today's solar panels and EVs is developing a comprehensive circular economy ecosystem to ensure that all future clean energy technologies are built to last, are repairable when they break, and are readily repurposed or recycled at the end of their useful lives. The long-term benefits of building clean energy technologies to last are massive: One study found that product lifetime extension strategies could reduce the amount of resource extraction required for metals to support the electricity sector by 13% in 2050, with additional reductions possible if combined with other circular economy strategies.[254] In the transportation sector, product lifetime extension could reduce resource extraction for metals by 8% in 2050 and, when combined with other circular economy strategies, cut demand for metals resource extraction by as much as 60%.[255]

Extending the lifetimes of rapidly advancing clean energy technologies does create some tensions. In some cases, technological improvements might result in a new wind turbine or solar panel being much more efficient at producing energy than one installed 15 or 20 years ago. Solar panels and EV batteries also degrade over time, which, coupled with policies that incentivize the adoption of clean energy, may further encourage individuals and businesses to upgrade to new technology. Therefore, in addition to making it possible for consumers to hold on to clean energy technologies for a longer period of time, policymakers should work to establish viable "second-life" applications.

Solar panels

Expectations for the useful life of solar photovoltaic (PV) panels have improved over time – increasing from 21.5 years for utility-scale systems installed in the U.S. in 2007 to 32.5 years in 2019.[256] However, to date, the vast majority of solar panels reaching the end of their lives have wound up in landfills.[257]

Repairing or reusing solar panels reaching the end of their lives, along with designing them for easier disassembly and recycling, could reduce demand for new panels. Assuming a lifespan of 25 years, the 4.95 GW of solar PV panels that had been installed worldwide before or in 2005 would reach the end of their lives by 2030.[258] Replacing those panels with new ones would require approximately 22,770 metric tons of copper.[259]

As solar energy deployment continues to increase dramatically, the importance of product lifetime extension and other circular economy approaches rises as well. A study by researchers from the National Renewable Energy Laboratory found that the nation would need to install a total of 1.2 *additional* terawatts of solar PV capacity in an aggressive decarbonization scenario if the average lifespan of panels is 15 years as opposed to 50 years.[260] In the event that none of those panels were recycled, demand for virgin materials for those panels would be 71% higher through 2050, a difference of 67 million metric tons.[261]

Repair strategies can enable existing solar panels to remain in use longer, and to prepare them for "second-life" applications.[262] Yet, lifetime extension has been little-studied compared with recycling as an approach for reducing the material demand of PV systems. Encouraging the development of markets for used and refurbished solar panels can help America to get a few more years out of the solar panels we have already built.

Wind turbines

Like solar energy systems, expectations for the lifespans of wind turbines have increased over time.[263] However, many wind farms experience either partial or full "repowering" before the end of their useful lives. Partial repowering involves the replacement of some wind turbine components – including, at times, components containing rare earth elements – with newer and often more advanced technologies. [264] Full repowering involves essentially rebuilding the wind farm on the same footprint with new turbines.

The gearbox-based wind generators that dominate the U.S. land-based market use fewer rare earth minerals than those reliant on large permanent magnets common in offshore wind (12 kg/MW of neodymium for gearbox-based generators vs. 180 kg/MW for permanent magnet-based systems).[265] Still, with 30 GW of onshore wind turbines potentially being repowered by 2028, the amount of material involved is significant.[266]

At present, few if any permanent magnets from wind turbines are recycled at the end of their lifespans, though there are some promising technologies that could change that.[267] Therefore, extending the life of wind turbines can make an important difference, with one study estimating that extending the lifespan of wind turbines from 20 to 25 years reduces rare earth demand by 15%.[268]

Policymakers need to weigh the trade-offs of the additional wind energy generated through repowering with any additional resulting rare earth mineral demand and encourage the reuse and recycling of wind turbine components containing rare earths and other critical minerals.

Second-life EV batteries

Extending the lifespan of electric vehicles through careful care, maintenance and judicious use[269] – and designing future electric vehicles and batteries to last – can reduce the demand for new EV batteries.

The market for energy storage is booming in the United States and around the world. Installations of energy storage nearly doubled from 2022 to 2023 and are projected to continue to grow over time.[270] Total energy storage capacity worldwide (not including pumped hydroelectric storage) is anticipated to exceed 1 terawatt-hour by 2030, most of it provided by lithium-ion batteries.[271] At the same time, the volume of spent batteries from electric bikes, cars, trucks and other vehicles is expected to reach 100 GWh globally by 2030 and increase to more than 400 GWh by 2035.[272] Should end-of-life EV batteries be able to be repurposed for energy storage – as is currently being demonstrated in projects around the world[273] – the world could either reduce minerals demand for energy storage or accelerate the deployment of a clean grid.

Lifetime extension and second-life applications for electric vehicle batteries are particularly important for managing future demand for lithium, which is not as widely used in the economy as metals such as copper and nickel and not as ready a target for materials substitution in batteries as cobalt. Currently, 97% of the market for grid-scale energy storage is accounted for by lithium-ion batteries.[274]

Other opportunities

In addition to consumer electronics and clean energy technologies, many critical minerals are widely used in other areas of the economy. Permanent magnets are used in many open-bore magnetic resonance imaging (MRI) machines, which make up approximately 25% of the MRIs in the United States.[275] The magnets for just one of these machines can weigh up to nearly 3,000 pounds, of which about 800 pounds is neodymium and 36 pounds is dysprosium. [276] One study estimated the volume of neodymium that could be recovered from end-of-life MRI machines in the U.S. at 60 tons in 2022, declining over time to 14 tons in 2030. [277] To the extent that these machines would be replaced by similar ones at the end of their useful lives, measures to extend their useful lives including medical "right to repair" can make a contribution to reducing demand for rare earth minerals.

Another potential opportunity is with nickel. The majority of the nickel used in the Western world is in the manufacture of stainless steel and certain metal alloys, not for clean energy.[278] While the type of nickel used in stainless steel is of a lower grade than that used in batteries, the markets for lower- and higher-grade nickel do intersect,[279] especially given the increasing use of technology that allows the conversion of lower-grade ore into the high-purity metal required for batteries.[280] Measures to reduce demand for stainless steel and other nickel-intensive products, including through recycling and product lifetime extension, could help to reduce the effects of any nickel shortages that might emerge in coming years.

America's homegrown critical mineral resources

America is uniquely positioned to benefit from circular economy strategies such as product lifetime extension as the world scrambles to amass the minerals necessary for the clean energy transition. The products we own, the wastes we produce and the toxic by-products of centuries of industrial production are critical resources the nation can and should tap in order to meet the needs of the emerging clean energy economy.

Getting the most use out of the products and infrastructure we have already built is among the surest ways to head off any short-term supply challenges for critical minerals in the critical years to come, and must be an essential part of building an economy that harnesses clean energy while fostering a healthy environment.

Strong leadership by governments, institutions, businesses and the public can help America and the world achieve that goal. The future is in our hands.

Recommendations

The world is at a crossroads. We can choose to build a new energy system the same way we built the old one, by maximizing the destructive extraction of resources from ecosystems we do not adequately value or fully understand, creating lasting harm for generations to come.

Or we can choose to tap other resources that we already have in abundance – including the human capacity for innovation, our ability to extend the useful lives of the products we have already created, the massive resources available in the "waste" from consumer industrial society – to minimize the impact of the clean energy transition on both terrestrial and marine environments alike. By doing so, we can live into the promise of a world powered by clean, truly sustainable forms of energy.

Getting there, however, will require a sea change in law and policy, as well as new approaches by policymakers, businesses and individuals. Among the most important steps are the following:

Preventing deep-sea mining

While some individual nations, such as Norway, are considering measures that would open up their national waters to seabed mining, the international community, through the International Seabed Authority, is considering proposals that would open up the seafloor to mining in international waters within the next several years – unleashing a mineral rush on the seafloor that may be difficult or impossible to reverse, regardless of its environmental consequences. At the same time, a coalition of other states are calling on the ISA to institute a precautionary moratorium on seabed mining.

The U.S. government and American businesses can play an important role in slowing or preventing the commencement of deep-sea mining:

- The U.S. government should provide diplomatic support for a precautionary pause or moratorium on deep-sea mining in international waters. More than two dozen nations have called for a precautionary pause or moratorium on deep-sea mining.[281] The United States is not a member of the International Seabed Authority, as it has not ratified the United Nations Convention on the Law of the Sea. But while the U.S. does not have a formal say in ISA decision-making, America can lend its voice to those countries urging a delay to, or outright moratorium on, the start of deep-sea mining.
- The National Oceanic and Atmospheric Administration should produce a report on the likely impacts of seabed mining on deep-sea ecosystems and marine life.
- The U.S. Congress should institute a precautionary pause or moratorium on seabed mining in U.S. territorial waters, and on processing of minerals obtained by seabed mining in U.S. states or territories.
- The U.S. Congress should reject any efforts to subsidize or incentivize deep-sea mining, and ensure federal agencies are not subsidizing, financing or incentivizing seabed mining projects or the processing of seabed minerals.
- U.S.-based corporations should commit to not using materials from deep-sea mining in their products, and U.S.-based financial institutions should not finance, insure or otherwise support deep-sea mining operations.

Extending product lifetimes

Extending the lifetimes of the products we use – especially consumer electronics, clean energy technologies and other products that use large amounts of critical minerals – can alleviate pressure for additional resource extraction. Critical steps to make this a reality include:

- Banning disposable electronic products with nonreplaceable batteries. This includes products such as disposable vapes.
- Empowering people to fix the stuff they own by enacting "right to repair" laws that require manufacturers to provide the information, tools, parts and resources needed to repair products when they break. Right to repair is essential not just for technologies that currently use critical minerals – such as smartphones, electric vehicles and medical technologies – but also for the many technologies that will soon incorporate batteries or computers, such as farm equipment.
- Encouraging products to be designed for repair by providing repair scores for consumer products. The French government, for example, rates a series of consumer products based on the ease with which they can be repaired.[282] A similar rating system could be designed to rate product durability.
- Requiring tech companies to provide software support to allow otherwise working devices to continue to operate, or, alternatively, to provide open access to software to allow innovators and the public to develop ways to allow those products to continue to be used. Out-of-date software should never be the reason that an otherwise-useful device is sent to the landfill.

Building a circular economy

Extending product lifetimes is just one part of a broader "circular economy" approach to materials that makes use of the "5 Rs." Reducing the amount of critical minerals we use through energy efficiency, encouraging "second-life" reuse of clean energy technologies, expanding recycling, and reimagining products to use fewer critical minerals and last longer are also critical steps. Among potentially important steps are the following:

- Encourage "second-life" applications for electric vehicle batteries and retired solar panels. Incentives that encourage the early retirement or repowering of clean energy technologies should balance the impact on critical minerals demand with increased energy production.
- Dramatically improve systems for collecting and recycling electronic devices and encourage the development of systems that ensure the collection and recycling of electric vehicle batteries, solar panels and other clean energy technologies at the end of their useful lives.
- Investigate the use of industrial waste for critical minerals. At best, tapping sources such as coal ash and aluminum production waste for critical minerals could reduce the danger those waste streams pose to the environment while helping the nation to meet its critical mineral needs. However, such approaches must not pose risk of additional environmental harm and should not further incentivize damaging modes of industrial production.
- Local, state and federal policy should seek to increase the energy and materials efficiency of transportation, industry, buildings and systems for producing energy. Energy efficiency policies and policies that reward materials efficiency in industrial production and product design can reduce the amount of critical minerals needed to power the clean energy transition.

Reducing damage from terrestrial mining

Terrestrial mining for critical minerals is likely to increase in the years to come regardless of whether deep-sea mining takes place. In addition to limiting demand for future terrestrial mining through circular economy strategies, the world must ensure that any new mining poses as little threat as possible to communities and the environment. Reforming mining laws to enhance environmental protections and supporting the adoption and enforcement of global standards for environmental responsibility in mining are essential to ensure that the transition to clean energy delivers the greatest benefit for the environment, public health and safety.

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