Article

Critical Mineral Challenges Complicate a Rapid Clean Energy Transition

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Abstract

A clean energy transition is accelerating, driven by increasingly ambitious policy goals. Yet the more ambitious the clean energy scenario, the greater the required volumes of copper, lithium, rare earths and other critical minerals. Even current rates of deploying solar, wind, transmission, storage and electric vehicles (EVs) are challenging mining and refining capacities for select critical minerals. Policy initiatives to address critical minerals are increasing apace, but mining is characterized by decadal time scales. Thus, policy change is unlikely to have much impact over at least the next decade. The result is that energy-transition will take longer than is generally thought and will almost certainly have to include painful tradeoffs so as to maximize decarbonization at least cost in critical minerals.

Keywords: critical minerals, mining, clean energy, decarbonization

"The transition to clean energy means a shift from a fuel-intensive to a material-intensive system" (IEA, 2021).

Critical Minerals: Introduction

This paper argues that the ongoing clean energy transition, though driven by increasingly ambitious policy goals, is almost certainly going to be delayed. The more ambitious the clean energy scenario, the greater the required volumes of copper, lithium, rare earths and other critical minerals. Even current rates of deploying solar, wind, transmission, storage and electric vehicles (EVs) are challenging mining and refining capacities for select critical minerals. Rapidly bolstering these minerals' upstream supply chains is imperative, but is complicated by mining's long lead times, underinvestment in new mining projects, environmental

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impacts, local and ESG opposition to mining, and the geopolitical risks of geographic concentration. These issues are compounded by large knowledge gaps concerning the volume of materials needed for clean energy in addition to such material-intensive sectors as national defence, digital transformation, and sustainable development in the Global South. Recycling, substitution, and other strategies are often adduced as counter-measures, but are of limited effect over meaningful time-scales. Policy initiatives to address critical minerals are increasing apace, but mining is characterized by decadal time scales. Thus, policy change is unlikely to have much impact over at least the next decade. The result is that energy-transition will take longer than is generally thought and will almost certainly have to include painful tradeoffs so as to maximize decarbonization at least cost in critical minerals.

Critical Mineral Lists and Issues

Critical minerals do not have a common global definition, but they are indispensable. They are defined in at least 15 national and regional lists of commodities assessed as strategic to clean energy, high-technology (microchips, health-care equipment, aerospace, and others), and weapons systems for national defence.[1] One major factor in determining a commodity to be critical are supply-chain risks, particularly risks stemming from the relevant commodity's geographical concentration of mining and refining. Most energy-related critical minerals – particularly lithium, nickel, rare earths, platinum group metals, cobalt, manganese, aluminum (bauxite), and graphite – overlap among the 15 lists. And copper is increasingly a focus of attention – and defined as a critical mineral by Canada and the European Commission – because it is the essential enabler in electrification (Mills, 2023). Indeed, in July of 2023 the US Department of Energy released its 2023 Critical Minerals Assessment, which included copper as a key material for clean energy and with a high risk of disruption (US Department of Energy, 2023).

Extracting and processing critical minerals requires very large capital investment and often entails significant environmental costs. Many critical minerals are also difficult to substitute for and recycle, at least over the next two decades of accelerated energy transition. These and other complications make it difficult to reduce the generalized (and in many respects, increasing) Chinese dominance of the critical mineral mining and refining supply

1) The most recent and comprehensive summary of critical mineral lists is Calvino (2022). However, in June of 2023 India released its first-ever list of critical minerals. On this, see Ministry of Mines (2023).

chains that are essential to clean energy. One indication of increasing Chinese dominance was seen in a mid-2023 study from the Green Finance & Development Center at Fudan University in Shanghai. The August 1, 2023 *Financial Times* reported that this study indicated Chinese investment in mining and metals for the first half of 2023 exceeded USD 10 billion. That figure was greater than the total investment in 2022, and suggested that full-year 2023 spending could overtop China's previous record of USD 17 billion in 2018 (White, 2023). At the same time, mounting financial and political constraints impede action by global mining firms. Concerning copper, for example, analysts warn that "the number of projects at or near a final investment decision from mining companies is lower than historical averages as hurdles to developing new copper projects increase" (White and Hook, 2023).

There are also very large knowledge gaps concerning critical minerals. One obvious gap is the calculation of required volumes for each of the critical minerals. For example, most decarbonization pathways tend to examine specific technologies, such as solar and wind or EVs, thus overlooking the sheer scale of emerging global demand for energy-generation, storage and transmission assets, and EV charging devices (S&P Global, 2022). Admittedly, these calculations are extremely difficult to undertake. One major hurdle is in seeking to model the future mix of solar, onshore wind, offshore wind, nuclear power, and other clean energy. Another impediment to accurate modeling is the sheer diversity of demand within each category. For example, the amount of copper required in offshore wind projects varies by the size of the turbines, their distance from shore installations, and in many cases also the distance between power generation and its consumption. And EV battery chemistries vary considerable in their respective mixes of lithium, nickel, and other materials. A further problem derives from myriad uncertainties in policy change, technological advances, and other factors that will shape the future profile of each individual critical mineral demand.

Another knowledge gap derives from a variant of the streetlight effect. Almost all surveys of critical mineral demand centre on needs for the energy transition. Moreover, most of these surveys focus on the advanced economies and China, where 90% of present clean energy investment takes place (IEA, 2023) and most analysts are located. Such surveys therefore downplay if not entirely overlook the clean energy needs (or wants) of roughly 5 billion people outside the advanced economies and China. They also overlook the developing world's demand for critical mineral-intensive devices used in communications, health care, education, and other sectors essential to equitable and sustainable development. In this regard, the Deputy Director of the Intergovernmental Forum on Minerals, Mining and Sustainable Development points out that "a significant portion of future demand for minerals and metals will come from other sources: the Fourth Industrial Revolution, driven by digital technologies, and perhaps more importantly, developing countries' demographic growth and organic industrial needs, is extraordinarily resource intensive" (Ramdoo, 2022). While it may be the case that these sources of non-energy critical mineral demand are a small fraction of the volume needed for energy, it is unwise to assume that to be the case.

Critical mineral surveys also disregard military-related demand. This oversight also seems unwise, as experts caution that annual US military demand for rare earths alone (a subset of critical minerals) is about 3000 tons. That volume is a sizeable fraction of the 10,000-15,000 ton per year of rare earths consumed by the entire US economy (Lifton, 2023). The Hague Centre for Strategic Studies also warned in January 2023 that European defence needs faced especially high materials risks in the aluminum, graphite, and copper used abundantly in clean energy (Girardi, et al., 2023). But in spite of military budgets rising 3.7% globally to USD 2.24 trillion in 2022 – with the steepest increase in Europe in three decades (SIPRI, 2023) – there is as yet no summary data on the defence sector's impacts on critical minerals. The risk of conflict between military and climate-related demand for critical minerals was highlighted in an April 18 2023 communication by the RAND Corporation, a key agency in assessing US military and other public policy challenges. Its warning stressed that "[n]either the United States—nor any other country—wants its national security needs to be in competition with its future climate security. But if both necessities are competing for too little raw material, the price pressure on these commodities and specialty chemicals could be damaging to both endeavors" (Villalobos and Bazilian, 2023).

These risks were brought into stark relief in July of 2023, when China announced it would begin restrictions on exports of gallium and germanium, critical minerals that have many applications in military and clean energy technologies. The restrictions began on August 1 of 2023, and it is unclear how long they will continue. But on August 3 the US Center for Strategic and International Studies warned that gallium's "unique properties allow for the production of specialized semiconductors that are vital to advanced capabilities like next-generation missile defense and radar systems, as well as electronic warfare and communications equipment. Disruptions in the gallium market could pose significant challenges for U.S. and allied defense industries and cost hundreds of billions of dollars in economic losses" (Funaiole, M. et al., 2023).

A further knowledge gap is in the economic impact of accelerating energy transition via aggressive state policy. This kind of analysis has been lacking due to the overriding narrative that no cost is to great because the fate of the planet is at stake. But experts on macroeconomic policy warn that rapid shifts of investment, especially in the EU, "threaten to create a stagflationary environment where brown energy is scarce and green energy is still in short supply. Coping with such imbalances will be an ongoing challenge for governments and central banks. Policymakers can no longer afford to overlook these issues, nor can they rely on fairy tales about what the energy transition entails. To convince citizens, they will have to define and implement a realistic agenda for managing the costs and complexities of the transformation" (Pisani-Ferry, J and S. Mahfouz, 2023).

The upshot is that the global specialist community is increasingly aware that demand for critical minerals is almost certainly poised for an accelerated and protracted "supercycle" increase (Bentley, et al., 2023). But modeling the timing and scale of the increase is beyond current fragmented assessment capacities. This enormous uncertainty impedes the transmission of crucial signals to key constituencies: to governments that they must ease regulatory barriers to mining and refining, to market players who need to allocate capital to new mining, to academic institutions that must bolster programs for training increasingly scarce human resource (geologists, miners, traders, and so on), and to the most ardent advocates of energy transition who need to accept that critical mineral mining must be increased. This last item is of especial concern to the mining industry, whose view "is that many of the people demanding an energy transition the loudest are the very same people working hardest to make it virtually impossible to produce the necessary metals" (Russell, 2023).

Critical Minerals and Clean Energy

Decarbonization via clean energy has become a primary focus of international agreements and country-level public policy commitments. Fossil fuels represent 82% of the increasing primary energy demand for the global population of over 8 billion, and the extracted volumes of coal, oil and natural gas exceed 15 billion metric tons (Bhutada, 2023). Decarbonization scenarios generally focus on electricity and seek to electrify currently fossil fuel-based mobility and such industrial processes as making steel, ammonia, cement, and other pillars of industrialization. The clean energy alternatives to coal and other fossil fuels centre on renewable energy, nuclear power, various means of producing low-carbon hydrogen/ammonia, capturing carbon from combustion and using it as a resource, and a growing portfolio of other approaches (IEA, 2022). The clean energy systems require far greater volumes of critical mineral inputs – per unit of generating capacity, per unit of generated power, per vehicle, and so on – than does building the infrastructure of conventional, carbon-intensive fossil energy. And the critical mineral footprint of solar, wind and other variable[2] renewable energy is especially high per unit of generated power (ie, kilowatt-hours as opposed to kilowatts) in addition to ancillary systems such as transmission and storage networks.

In 2022, global critical mineral demand for energy-related systems alone was assessed as about 7 million tons, and even moderate decarbonization efforts are expected to require a quadrupling of that annual flow by 2040 (Bazilian and Brew, 2023). Accelerated decarbonization will require even more. Even so, many advocacy coalitions and analysts insist that inadequate political will is the only impediment to a dramatically accelerated energy transition centred on variable solar power and wind generation (Jacobson, 2023). They dismiss critical mineral issues and argue that renewables offer the cheapest means of cutting GHG emissions. Some observers concede that critical minerals are required, but assert that global mining can readily replace the extraction of billions of tons of fossil fuels for mining and refining millions more tons of critical minerals (Bond, 2021). For example, Leonardo Buizza, Lead Supply Chains and Materials Analyst at the Energy Transition Commission (a coalition of business and expert interests) asserts that mining investors need only shift their perceptions in light of the Commission's 2023 survey of critical minerals. The survey is optimistically interpreted as revealing that "the energy transition will require the production of 6.5 billion tonnes of end-use materials, 95% of which would be steel, copper and aluminium, with much smaller quantities of critical minerals/materials such as lithium, cobalt, graphite or rare earths between 2022-50. This cumulative material extraction compares with the over 8 billion tonnes of coal currently extracted annually, with global unabated coal use in the energy system forecast to fall by around 55% under the Net Zero Emissions by 2050 scenario" (Fronda, 2023). Other analysts similarly suggest that critical minerals are not a significant concern because the energy transition's projected demand for critical minerals does not exceed assessed geological reserves (Wang, et al. 2023). All these perspectives overlook the logistical challenges of mining and refining escalating volumes of critical minerals.

Mining and refining a lot more critical minerals are dramatically different from the ongoing extraction of billions of tons of fossil fuels. A given volume of critical minerals requires

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2) "Variable" as used here refers to the fact that solar and wind technologies only generate power when the sun shines or the wind blows. These variable renewables thus have low "capacity factors," or percentage of actual operating time over a year. Thus their actual power generation (eg, kilowatt-hours) is often only 10%-30% of their nameplate capacity (eg, kilowatts). Solar and wind are distinct from nuclear, hydropower, geothermal and other generation assets with far higher capacity factors, which provide far more electricity production per unit volume of critical minerals used in their construction.

the extraction and processing of orders of magnitude of ore. In copper mining, for example, average ore grades of new mines are below 0.5%, meaning that each ton of copper requires extracting and processing 200 times that volume of overburden (Keen et al., 2022). Since global copper mine production in 2022 was about 22 million tons, that equates to 4.4 billion tons of overburden, a volume that is on approximately equal to annual global oil production and just less than half total global coal production. It is thus misleading to suggest that the shift from a fuel-based to a material-based system is quite logistically simple.

Ramping up critical mineral production therefore entails an enormous and expensive expansion of mining and refining. Moreover, mining and refining of critical minerals do not respond in lockstep with policy signals and decarbonization scenarios. Thus in 2021-2022 an accelerated deployment of intermittent renewable energy quickly encountered supply shortages and price increases. The costs of lithium, copper, and other materials remain quite elevated relative to their historic averages. After more than a decade of dramatically declining costs for batteries, solar panels, and wind turbines, prices rose in 2022 due to critical mineral costs (BloombergNEF, 2022; Kim, 2022). In addition, Jose Fernandez, US Undersecretary of State for economic growth, energy and the environment warned on July 20 2023 that "[w]ithin a decade, shortages of critical minerals such as lithium, graphite and copper will increase prices and slow the deployment of clean energy technologies" (Northey, 2023).

Critical Raw Materials and Clean Energy

The International Energy Agency's (IEA) 2021 report on *The Role of Critical minerals in Clean Energy Transitions* remains the most comprehensive analysis of energy-related critical mineral demand and supply (IEA). The IEA assessed supply and demand data for copper, silicon, nickel, lithium, rare earths, and other critical mineral used in16 clean-energy technologies, including solar, wind, and nuclear. The IEA's careful empirical work shows that the more rapid the decarbonization, especially if led by intermittent renewable, the greater the demand for critical minerals. The IEA thus warns that emerging bottlenecks make collaborative action urgent.

Figure 1 outlines the range of energy technologies the IEA assessed and their dependence on select critical minerals. The degree of dependence is visible in black, grey and white dots, respectively indicating high, medium and low reliance. Critical mineral dependence is especially marked for electric vehicles (EVs) and battery storage. And among power generation technologies, variable solar and wind require much higher densities of critical

	Copper	Cobalt	Nickel	Lithium	REEs	Chromium	Zinc	PGMs	Aluminium*
Solar PV	●	○	○	○	○	○	○	○	●
Wind	●	○	◐	○	●	◐	●	○	◐
Hydro	◐	○	○	○	○	◐	◐	○	◐
CSP	◐	○	◐	○	○	●	◐	○	●
Bioenergy	●	○	○	○	○	○	◐	○	◐
Geothermal	○	○	●	○	○	●	○	○	○
Nuclear	◐	○	◐	○	○	◐	○	○	○
Electricity networks	●	○	○	○	○	○	○	○	●
EVs and battery storage	●	●	●	●	●	○	○	○	●
Hydrogen	○	○	●	○	◐	○	○	●	◐

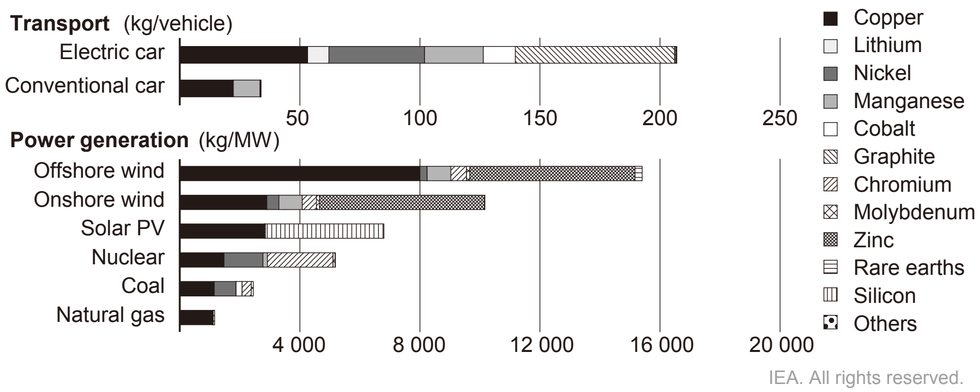
Source: IEA (2021).

Figure 1 Critical Minerals in Clean Energy Technologies

minerals than do 24/7 hydro, geothermal and nuclear. Electricity networks – which includes transmission lines – also require large amounts of copper and other critical minerals. Wind and solar power projects cover a lot more area than spatially small nuclear, and thus have even higher critical mineral "system costs," since networking their dispersed power generation requires a lot more power lines and other assets. Indeed, the July 30 2023 *Financial Times* highlighted the demand for electricity networks as an emergent area of serious concern, hitherto generally underestimated if not entirely overlooked. It warned that "[d]emand for interconnectors and other energy infrastructure such as wind turbines is growing rapidly, putting unprecedented strain on supply chains for electricity cable and the converter stations needed for connection to the grid" (Millard, 2023).

Critical Minerals, Electric Vehicles and Power Generation

Figure 2 provides a comparative quantification of critical mineral density for EVs and clean power generation. The figure's top section ("Transport") reveals that an average EV is dramatically more material-intensive than a conventional car. In 2022, the total global fleet of conventional vehicles included about 1.2 billion passenger cars, whereas the total global EV fleet perhaps reached 27 million compared to 1 million in 2016 (McKerracher, 2022). Electrification of transport is unfolding rapidly but still only in its infancy. The critical mineral challenge stems from the fact that the average EV requires over 206 kilograms (kg) of



Source: IEA (2021).

Figure 2 Minerals Used in Select Clean Energy Technologies

critical minerals per vehicle. By contrast, the average conventional car requires just under 34 kg of critical minerals. In short, the average EV is over 6 times as mineral-intensive. Small wonder that in May of 2023 a survey led by Chalmers University of Technology, Sweden, for the European Commission, warned that supplies of the critical metals required for EV batteries and other components is clearly inadequate, even with increases in recycling (Ljunggren, 2023).

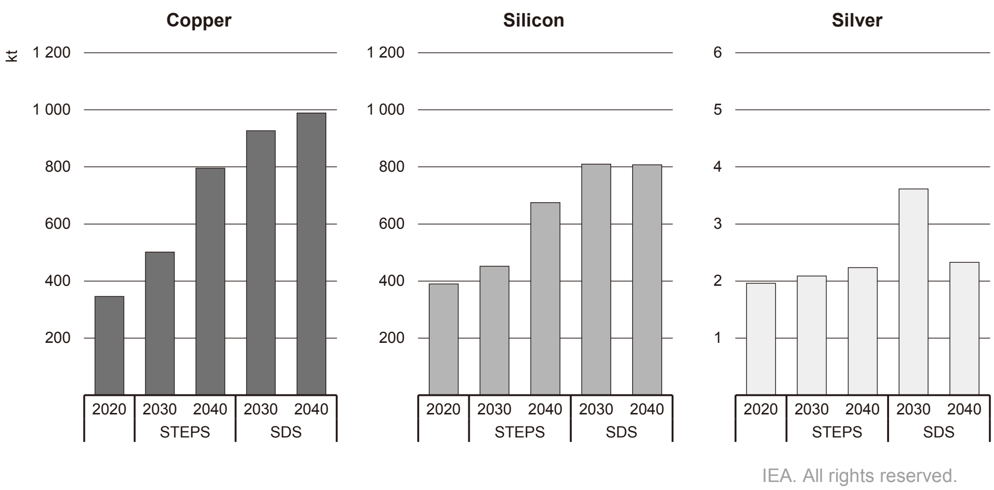
Variable renewable energy entails similar complications. Figure 2's lower section ("Power generation") reveals that renewable and nuclear power generation technologies have significantly higher material-density than fossil (coal and natural gas), expressed as kilograms/megawatt (kg/MW) of generation capacity. Building natural gas and coal-fired generation plant requires only moderate amounts of copper, nickel and other critical minerals. By contrast, building a conventional nuclear reactor uses, per-MW of capacity, more than double the critical mineral footprint of a coal plant and triple that of a natural gas generation asset. Variable renewables are even more dependent on critical minerals. Solar and onshore wind generation both rely much more on copper, followed by silicon for solar and zinc for onshore wind. And offshore wind is especially dependent on copper and zinc, in addition to rare earths for their permanent magnets. In consequence, the per-MW critical-mineral footprint balloons from a couple of metric tons for a natural gas plant to nearly 16 tons for offshore wind.

Adding to the complications, variable wind and solar have considerably lower capacity factors – meaning percent of actual power generation versus rated generation capacity – than fossil-fuel and nuclear plant. Therefore, the total volume of critical minerals they require to produce a given amount of electricity is even higher than expressed in the figure.[3]

Critical Minerals in Solar Power

The data in figure 3 offers more detail on solar panels' reliance on three key critical minerals between 2020 and 2040. It displays in kilotons (kt) the 2020 demand for copper, silicon and silver in global solar deployments, exclusive of such system requirements as storage and transmission equipment. The figure estimates solar's increased demand for the three materials according to two scenarios: the Stated Policies Scenario (STEPS), which implies global warming of over 3 degrees Celsuis; and the Sustainable Development Scenario (SDS), whose aim is to limit global warming to under 2 degrees Celsius, and ideally to no more than 1.5 degrees. STEPS and SDS are used throughout the IEA's report and within several figures below.

Figure 3 shows that the SDS and STEPS scenarios for solar vary greatly by 2030 and 2040. Solar's demand for copper more than doubles from its 2020 level of roughly 370 kt to just under a million tons in SDS 2040. The demand for silicon also doubles from nearly 400 kt



Source: IEA (2021).

Figure 3 Demand for Copper, Silicon, and Silver for Solar PV by Scenario

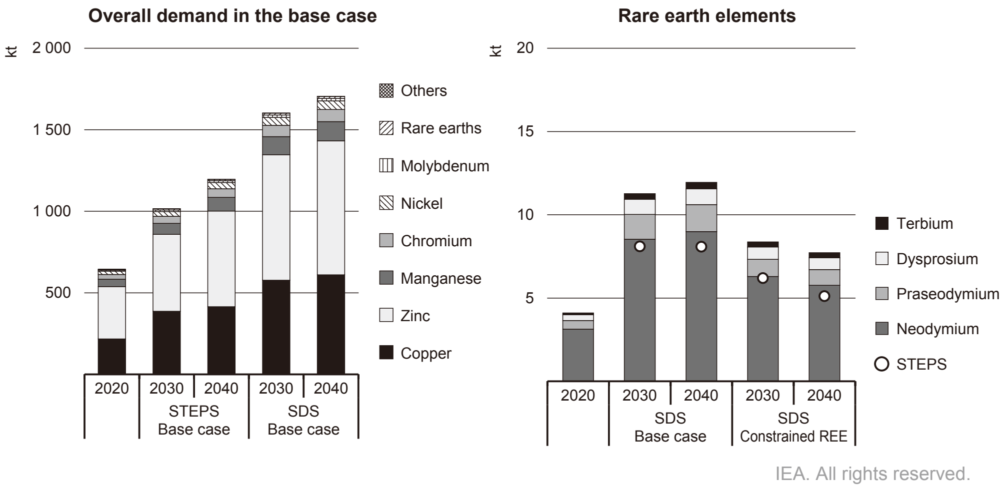
3) For example, a 2021 study by the United Nations Economic Commission for Europe (UNECE) determined that nuclear power requires 84 grams of select CRITICAL MINERAL per megawatt-hour (MWh) of generated power, whereas solar technologies need between 296-635 grams/MWh and wind power uses between 255-292 grams/MWh. See UNECE, 2021, p. 55.

in 2020 to over 800 kt in SDS 2030, later leveling off through technological change and recycling.

In addition, the IEA projects that silver demand will rise from nearly 2 kt in 2020 to over 3.5 kt in the SDS 2030 scenario, which presents serious difficulties because solar's call on global silver in 2020 was already 12.7% and rising dramatically (Hallam, et al., 2022). Indeed, analysts now warn that industrial demand for silver, "largely from solar, will make up 53% of total demand from 2025" (Chiat, 2023).

Critical Minerals in Wind Power

Figure 4 illustrates critical mineral demand from onshore and offshore wind power in 2020 and then out to 2040. The left-hand side of the figure shows that demand for copper, zinc and others nearly triples between 2020 and 2030 in an SDS scenario. The right-hand side of the figure details demand for wind-related rare earth elements (REE), estimated to more than double 2020 levels in the SDS base case for both 2030 and 2040. The IEA estimates that there will be a large reduction in per-unit demand for REE (crucial to permanent magnets) via substitution, greater efficiency, and other measures. But even then, per-unit efficiencies are overtaken by the sheer scale of new deployments. Hence, the demand for essential REE – ie, terbium, dysprosium, praseodymium, neodymium – doubles by 2030. Wind is often seen as a complement to solar power in leading a low-cost and clean energy transi-



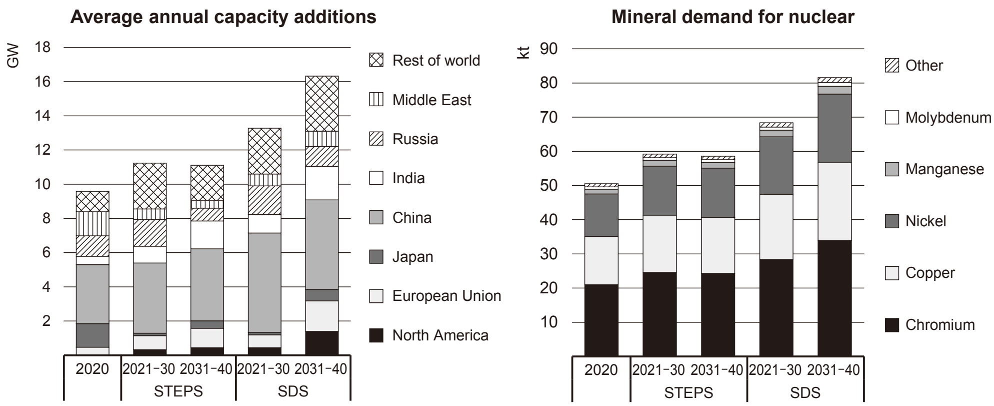
Source: IEA (2021).

Figure 4 Mineral Demand for Wind by Scenario tion. But wind requires very high volumes of critical minerals and the costs are increasing. Especially concerning is the April 2023 report that wind-turbine costs were up 38% compared to two years earlier, and that "[t]he average price of the seven most significant critical minerals for the wind industry has increased by 93% since January 2020" (Ferris, 2023).

Critical Minerals in Nuclear Power

Figure 5 summarizes anticipated capacity additions and critical mineral demand from nuclear power for STEPS and SDS scenarios. The figure shows that in 2020 new nuclear capacity additions were dominated by China, Russia and the Middle East, and entailed about 50 kt of critical minerals. A doubling of nuclear's average annual capacity additions, especially in China, underpins the 2040 SDS scenario. This assessment may be an underestimate, as China accounts for 23 of 55 nuclear projects under construction as of this writing (Murtaugh, 2023). Moreover, the US, France, Canada, and a host of other countries have introduced significant policy supports for new nuclear in addition to extending the lifetimes of operating nuclear assets.

The critical mineral demand from nuclear capacity additions for 2030 and 2040 SDS scenarios are slightly more than 80 kt. As we saw in figure 2, this critical mineral density per MW of generating capacity is far less than what is needed for solar and onshore/offshore wind, even if we disregard the larger power network (transmission, storage and other assets) required for variable renewables. Nuclear power has generally high capacity factors,



Source: IEA (2021).

Figure 5　Critical Minerals and Nuclear Power often reaching over 90% due to operators' skill in minimizing the time required for maintenance and refueling. Nuclear power therefore affords even better material-efficiency when viewed in terms of the volume of copper and other critical minerals needed to generate a given unit of electricity.

The Challenge of Unprecedented Volumes of Critical Minerals

The IEA data thus show that clean energy – and especially solar and wind – require large volumes of critical minerals per unit of output. In consequence, decarbonizing primarily through EVs and variable renewables entails massive critical mineral demand. Even the IEA's moderate STEPS scenario forecasts a doubling of solar deployment between 2019 and 2040, with corresponding increases in wind, electricity networks, and EVs. The IEA's more aggressive SDS scenario foresees a tripling of solar, wind, and electricity networks between 2020 and 2040, and a startling 25 times increase in EV diffusion. The result is at least a six-fold increase in critical mineral demand for clean-energy technologies. And it is important to underscore the fact that these are not net-zero scenarios.

The precise rate of increase for any particular critical mineral clearly depends on which clean-energy elements are emphasized. Hydropower and nuclear power assets deliver a lot of low-cost, low-carbon electricity with low critical mineral footprints, whereas variable renewables incur far higher critical mineral costs. And note that the SDS tripling of variable solar and wind by 2040 also requires a massive increase in utility scale battery storage. This deployment sees nickel demand for storage grow 140 times, cobalt by 70 times, and manganese by 58 times. Similarly, SDS by 2040 implies that 42 times more lithium must be produced over the next two decades, in addition to 25 times more graphite, 21 times more cobalt, 19 times more nickel, and 7 times more rare earths. Here too, increasing costs are becoming evident: "[b]attery storage costs are expected to rise in 2023, as average prices rose to about $200 per kilowatt-hour (kWh) in the first half of 2022, largely due to supply chain challenges, after declining for more than a decade to approximately $175/kWh in 2020" (Deloitte, 2023).

Critical Minerals: Geopolitical and ESG Issues

The world does not confront absolute resource scarcity on critical minerals. In July of 2023, the Energy Transitions Commission released a detailed report emphasizing that "[t]here is no fundamental shortage of any of the raw materials to support a global transition to a net-zero economy: geological resources exceed the total projected cumulative demand from 2022-50 for all key materials, whether arising from the energy transition or other sectors" (Energy Transitions Commission, 2023). There are abundant terrestrial reserves and resources, and many times that if we include the rich resources of critical minerals on or beneath the world ocean's floor. Yet it takes many years to build out the mining and refining capacity to extract critical minerals and render them useful as material inputs into production. Those steps are preceded by years of feasibility studies, environmental assessments, water and power infrastructure installation, and other costly site preparation. For example, developing a new copper mine requires an average of 16 years (Iannucci, 2022; IEA, 2021).

Geopolitical risks are another difficult challenge. The mining and refining supply chains of many critical minerals are generally even more dominated by a few countries than is the case with oil and gas. The U.S. and Saudi Arabia are among the largest fossil fuel producing countries, but have relatively small market shares of oil and natural gas (coal reserves are even more diversified). By contrast, China extracts 60% or more of rare earths and graphite, and controls 70% of global lithium refining. Moreover, 70% of cobalt production is done in the Democratic Republic of the Congo. The higher the concentration of critical minerals mining and refining, the greater the geopolitical risks for consumer countries. These risks include producer countries' incentives to raise royalties and restrict supply, further increasing critical minerals prices. Indeed, the OECD warned in April, 2023 that critical mineral trade barriers had quintupled over the previous decade (OECD, 2023). The IEA has also warned that geographically concentrated critical minerals supply chains risk their being used as a geopolitical weapon (Walsh, 2023). Geographic concentration also worsens supply-chain risks from strikes, natural disasters, conflicts, and other developments outside of producer-country control.

The G 7 and other actors seek to address concentrated supply chains with diversification, but that is far easier said than done. Critical mineral mining is very capital intensive and take a lot of time, meaning that mining firms are compelled to risk a lot of capital over many years while developing a project. Mining firms seek to alleviate their business risks through offtake agreements that commit customers (such as automakers) to long-term contracts for critical minerals. The number and length of these agreements is increasing, but the volumes are nowhere near the huge critical mineral demand implied in most decarbonization scenarios (Sebrell and Ivanov, 2023). It is therefore understandable that mining firms are not investing enough to meet the IEA's SDS scenarios or even more ambitious goals.

Thus specialists from the U.S. Center for Strategic and International Studies warn that "[t]here is little sign that the supposed 300 new mines needed to meet clean energy needs for cobalt, graphite, lithium, copper, and vanadium will be anywhere close to operational by 2030" (Berg and Ziemer, 2023). By contrast, in January of 2023 China's Ministry of Natural Resources committed to expanding support for overseas and domestic mining (Yutong, et al., 2023).

Unlike decarbonization scenarios that unfold on paper and at academic conferences, critical mineral mining projects take place in a real world of price volatility, local opposition, and other investment risks. By 2030, there could be a cumulative shortfall of copper equating to 50.5 million metric tons, or well over two years of current annual production. But mining firms have no guarantee of that estimate, and in any event policymakers in the developed countries tend to defer to anti-mining interest groups (Schaps, 2022). In consequence, it seems unlikely that there will be significant reshoring and other diversification of critical mineral mining and refining over the next decade.

Declining ore grades are a further complication confronting critical minerals. In Chile, home to over a quarter of global copper production, there has been a 30% decline in copper ore-grades from the mid-2000s to 2020. Declining ore grades mean that more ore must be extracted and processed to produce a unit quantity of copper or other critical mineral. The additional mining and refining raise the unit energy cost in addition to the volume of water. And a lot of critical mineral mining is situated in water-stressed areas (Galindo, et al., 2022). The result of declining ore-grade, increasing water stress, and other realities is that extraction is becoming more expensive and environmentally damaging (Bontje and Duval, 2022).

One example of damage is mine tailings. These are the waste left after refining separates the desired metal from the mined rock, leaving a slurry of particles mixed with water. This material is stored in settling ponds, whose global total is a staggering 217.3 km^3 that weighs 282.5 billion metric tons. Approximately 46% of global mine tailings derive from copper, with significant amounts also from other critical minerals (LePan, 2021). The mining and refining of rare earths also produce significant quantities of radioactive materials and other impurities (Bai, et al., 2022).

To be sure, these localized impacts of extracting copper and other critical mineral pale when set aside the rising global risk of climate change. But in the end, all politics is local, and thus policymakers and advocacy coalitions in the developed world want critical mineral-intensive EVs and other decarbonizing devices but not the voluminous critical mineral extraction necessary to make them.

What About Recycling and Substitution?

Since extraction and refining critical minerals is fraught with risks, an expanding literature on energy transitions calls for recycling in “circular economy” strategies to reduce the need for newly mined copper, cobalt, rare earths and other metals and minerals. Substitution strategies complement this approach, by seeking to us different materials in place of supply-constrained items used in batteries, solar panels, and other devices. Recycling and circular economy approaches are indeed core principles of the 7-country Sustainable Critical minerals Alliance[4] that was launched in December of 2022 (Natural Resources Canada, 2022) and were emphasized by the 2023 G7 communique relating to critical minerals.

But the IEA analysis does not expect recycling or substitution to play much of a role for at least a couple of decades. The IEA suggests recycled battery materials will cover at best 1% of demand by 2030 and only 8% of demand as late as 2040 (IEA, 2021). These forecasts are consistent with other assessments of critical mineral challenges (Deloitte, 2022; Zeng, et al., 2022).

One key constraint on recycling is the limited resource base. The deployment of clean energy has only just begun, meaning there is a limited stock of EVs, variable renewables, and other assets. Bloomberg New Energy Finance research shows that global spending on energy-transition infrastructure reached USD 1.1 trillion in 2022, over twice the volume of investment in 2019, and nearly quintuple the USD 241 billion a decade before, in 2012 (BloombergNEF, 2023). In gross material terms, those numbers mean a massive wave of new energy-transition infrastructure stock was deployed in 2022, well before previous years’ low volumes of EVs and other devices were even close to being retired and ready for recycling. Bloomberg predicts a rapidly increasing energy-transition investment in the coming years, but recycling can only become a significant source of material input after a very large infrastructure stock has both been deployed and then used for at least a decade (for an EV) or two (such as a solar array) or perhaps many decades (as with a nuclear reactor). The lifetimes vary according to the specific asset’s average useful life cycle and the specific conditions of its use.

Another difficult issue is recyclability per se. Many solar panels and other clean-energy technology is built to maximize performance rather than the ease of recycling. The devic-

4) As of this writing, the Alliance comprises Australia, Canada, France, Germany, Japan, the United Kingdom and the United States

es are often contain alloys and other critical mineral combinations that are difficult to recover (Graedel, et al., 2022). Remedying that fact will take time, thus adding to the years required before recycling leads to significant new flows of critical minerals.

To reiterate, data clearly show that the global community is only beginning to build a stock of energy-transition infrastructure, including long-distance networks, distributed grids, battery storage, electric vehicles, and offshore turbines. A huge stock has to be in place, with a significant share of it having reached the end of its useful life, before we can derive an appreciable level of critical mineral flows from recycling. Stronger policies on recycling and substitution surely need to be adopted, but those policies will not bear much fruit for many years, and perhaps decades. And it seems essential that those policies be coupled with new design rules that prioritize recyclability over appearance and possibly functionality as well.

Conclusions

We have seen that the clean energy transition is an unprecedentedly huge project. Cheap and abundant critical mineral supplies are essential to decarbonization, in tandem with achieving global goals on sustainable development. But it seems impossible to do that in the near and medium-term, whether relying on market mechanisms or even aggressive and collaborative industrial policy. It is quite hard to imagine that myriad domestic and international stakeholders could reach agreement on strategic prioritization of constrained critical mineral supplies.

Recent studies of critical minerals warn about the urgency of good governance through comprehensive and collaborative public policy. In addition, the IEA seeks to address knowledge gaps by creating and disseminating credible information on critical mineral supply and demand, but this has only started and is still largely constrained to energy in the developed economies and China. Like the G7, OECD, and other international agencies and initiatives, the IEA argues for clear policy goals to help alleviate the risks of critical mineral price volatility and other impediments to expanded mining and processing. Those recommendations for enhancing supply capacity are echoed in myriad studies. And on the demand side, virtually all studies promote recycling, substitution, and innovation. At the same time, we have seen that these measures will not have much effect for at least the next decade. Moreover, none of these agencies and initiatives has undertaken the massive analytical task of reconciling conflicting evidence in models. Yet on this point, experts from the highly regarded Columbia University Center on Global Energy Policy highlight that "[t]ools used for charting a course to net-zero scenarios need to better account for volatility, myopia, and uncertainty in critical mineral supply, as it becomes clear that the pathways to a net-zero energy system will be bumpy rather than smooth, as the best models currently estimate" (Moerenhout, et al., 2023).

At the international level, the IEA and others also emphasize coordinated governance in place of the current patchwork of international institutions and initiatives that address various aspects of critical mineral mining and processing. At present, most critical minerals are traded on very opaque markets, with a shortage of analysts who understand their intricacies. Building robust and ESG-compliant supply chains "would both compete with and complement existing supply chains. They will have to be built nearly from scratch in markets that are opaque, volatile, and vulnerable to manipulation" (Majkut, et al., 2023). In concrete terms, the G 7 and other international actors need to build up the institutions for monitoring supply chains, collecting and disseminating credible data, sharing knowledge and best-practices, and developing credible and actionable environmental standards (Hendrix and Bazilian, 2022). These kinds of actions are ongoing, of course, but will require significant time to deliberate and define the best options and then embody them in bilateral or multilateral agreements.

In other words, aggressive and coordinated public policy is certainly an essential condition for determining how to secure abundant supplies of critical mineral at acceptable financial and environmental costs. But defining good governance and building it is not a sufficient condition for securing the requisite critical mineral supplies, whose ramped-up mining and refining will inevitably take a lot of time. In consequence, price increases in variable renewables and EVs seem certain to escalate and become protracted as opposed to transitory (Kim, 2022). And for the myriad reasons discussed above, higher critical mineral prices do not readily lead to a lot of new investment in mining and refining. Time is becoming the scarcest commodity. The issues were succinctly summarized by Canadian mining expert Nelson Bennett: "The problem for Canada, the U.S. and Europe, all of which are developing critical mineral strategies, is that no amount of money can buy time. Emissions reductions targets set by numerous governments will require so much copper, cobalt, nickel, lithium and other critical metals for things like electric car batteries and wind turbines that the new mines needed to provide the raw materials probably can't be built in time to meet the targets" (Bennett, 2022).

There is virtually no prospect of large-scale substitution, recycling and other short-term, silver-bullet solutions to shortages, so it would appear that strategic prioritizing of the use of supply-constrained critical minerals will almost certainly become necessary (Deloitte, 2022). In the energy sector, these materially efficient approaches are likely to include smaller EVs (Bonasia, 2023), public transit over personal EVs (Gupta, 2023), large-scale solar over rooftop, and perhaps more hydro and nuclear to supplement intermittent renewables.

Deliberation about strategic tradeoffs on critical minerals is not animating discussion among the myriad stakeholders focused on decarbonization. At the same time, serious structural supply deficits are almost certain to emerge by 2025 in copper, the key critical mineral (S&P Global, 2022), in addition to nickel, rare earths, lithium, cobalt, and several others (Berg and Ziemer, 2023; Chetwynd, 2023). High prices thus seem likely to become the default tool for allocating among competing demands, further undermining political support for clean energy. It is unclear what impact this possibility could have on economic development and political stability in the Global South. But ahead of the COP28 climate talks in Dubai (during November 2023), indications are that China, India, and other major global players are already pushing back against G20 proposals to triple renewable energy use (Mooney, 2023). The result seems also certain to be a more expensive and protracted energy transition, and one that entails a lot more compromises than most scenarios imagine.

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