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# Mind the Gap: The Supply of Critical Minerals Versus the Demand from Climate Policies

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## Abstract

A global energy transition is deemed imperative by the climate science community and by most scientifically informed policymakers. But it is as yet unclear how to transition from conventional energy – in a world with roughly 82% reliance on fossil fuels – at least cost and maximum speed. Renewable energy and electric vehicles are generally portrayed as key to rapid decarbonization, but numerous issues impede their accelerated deployment. This paper examines the recent literature on such critical minerals as copper and rare earths, in an effort to determine whether their supply and demand pose a threat to decarbonization scenarios. We find that there are good reasons to be concerned, especially with respect to knowledge gaps regarding critical minerals.

## Introduction

Decarbonization of the global energy sector is recognized as imperative by the Intergovernmental Panel on Climate Change (IPCC),<sup>1)</sup> the International Energy Agency (IEA),<sup>2)</sup> the Organization for Economic Cooperation and Development (OECD),<sup>3)</sup> the

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1) “Summary for Policymakers,” in *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001

2) See, for example, “An updated roadmap to Net Zero Emissions by 2050,” International Energy Agency, <https://www.iea.org/reports/world-energy-outlook-2022/an-updated-roadmap-to-net-zero-emissions-by-2050>

3) F. D’Arcangelo, et al. (2022), “A framework to decarbonise the economy”, *OECD Economic Policy Papers*, No. 31, OECD Publishing, Paris, <https://doi.org/10.1787/4e4d973d-en>

International Monetary Fund (IMF),<sup>4)</sup> and other major international institutions. This is because in 2022 energy conversion and energy-intensive industry, transport, and other areas are estimated to compose 65%, or 45.7 gigatons (GT), of humanity's 57.8 GT of greenhouse gas (GHG) emissions.<sup>5)</sup> The GHG emissions data for 2022 was also the highest amount ever recorded, and emissions are also on an increasing trajectory. At present, GHG emissions are projected to exceed 62 GT by 2030. Yet the IPCC and other high-level analyses warn that GHG emissions must be reduced to 29.76 GT by 2030 in order to avoid global warming in excess of 1.5 degrees Celsius.<sup>6)</sup> There is no way to achieve the requisite GHG emissions reductions without dramatically changing the global energy mix, particularly by electrification of power, mobility and industrial heat in addition to deploying energy sources with minimal GHG emissions.

## The Global Energy Economy

The scale of the existing global energy economy needs to be appreciated before examining the proposals to change it. Too many analyses of energy alternatives point to one or another technological development – such as algal biofuels<sup>7)</sup> – as ready alternative sources of energy, without confronting two key questions of whether the technology can scale and whether its diffusion can be undertaken at reasonable cost in terms of land use, material requirements, and tradeoffs in reliability. It is not enough to point to climate and other costs that might be avoided in the future if costs in the present detract from achieving equitable health care, access to clean water, universal education, and other essential outcomes.

In 2022, the total value of global energy was estimated to be USD 10 trillion, or about

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4) Simon Black, et al. highlight the options in “Getting on Track to Net Zero: Accelerating a Global Just Transition in This Decade,” International Monetary Fund Staff Climate Note No 2022/010, November 4, 2022: <https://www.imf.org/en/Publications/staff-climate-notes/Issues/2022/10/31/Getting-on-Track-to-Net-Zero-Accelerating-a-Global-Just-Transition-in-This-Decade-525242>

5) See the summary and sectoral data at World Data Lab: <https://worldemissions.io>

6) Homi Kharas, et al. describe the increasing gap between GHG emissions and reductions required to meet the 2015 Paris Agreement target of at or below 1.5 degrees Celsius in “Tracking emissions by country and sector,” Brookings Blog, November 29, 2022: <https://www.brookings.edu/blog/future-development/2022/11/29/tracking-emissions-by-country-and-sector/>

7) On algal biofuels and their challenges, see Simin Tazikeh, et al., “Algal bioenergy production and utilization: Technologies, challenges, and prospects,” *Journal of Environmental Chemical Engineering*, Volume 10, Issue 3, June 2022: <https://www.sciencedirect.com/science/article/abs/pii/S2213343722007369>

10% of global GDP. Fully 80% of this cost was from fossil fuels.<sup>8)</sup> The global human population of over 8 billion derives roughly 82% of its prodigious and increasing energy demand through fossil fuels. In 2022, global coal consumption exceeded 8 billion metric tons for the first time ever.<sup>9)</sup> As to oil and natural gas, the previous year, 2021, is the most recent data as of this writing. That year saw the world consume 4.2 billion metric tons of oil<sup>10)</sup> and about 4.04 trillion cubic meters – roughly 3.35 billion metric tons<sup>11)</sup> – of natural gas.<sup>12)</sup> So overall, humanity's fossil fuel consumption exceeded 15.55 billion metric tons of mined and refined material. And these fuels were transported through a massive built infrastructure that included 403,000 kilometers of oil pipelines, 28,800 kilometers of natural gas liquids pipelines,<sup>13)</sup> 9,564 gas-fired power plants of 50 megawatts (MW) or higher capacity,<sup>14)</sup> over 8,883 oil tankers,<sup>15)</sup> and over 700 liquefied natural gas (LNG) tankers.<sup>16)</sup>

Numbers on such a scale mean little on their own, so let us engage in instructive comparisons. The total human consumption of cereal grains offers one example. And the data indicate that total global cereal production – including all maize, wheat, rice, and other grains – in 2022 was 2.756 billion metric tons, or only 17.7% of global fossil fuel consumption. An additional comparison can be found in the global consumption of cement and concrete, the

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8) Stephen Peake, “Our US\$10 trillion global energy bill dwarfs what’s needed to limit global heating,” *The Conversation*, November 28, 2022: <https://theconversation.com/our-us-10-trillion-global-energy-bill-dwarfs-whats-needed-to-limit-global-heating-194868>

9) See “The world’s coal consumption is set to reach a new high in 2022 as the energy crisis shakes markets,” *International Energy Agency*, December 16, 2022: <https://www.iea.org/news/the-world-s-coal-consumption-is-set-to-reach-a-new-high-in-2022-as-the-energy-crisis-shakes-markets>

10) The data are available at Statistica “Oil consumption worldwide from 1970 to 2021,” Statistica: <https://www.statista.com/statistics/265261/global-oil-consumption-in-million-metric-tons/>

11) The conversion factor for natural gas volumes to weight is  $1 \text{ m}^3 = 0.829 \text{ kilograms}$ . See “Weight units energy,” *Netherlands Statline CBS*: <https://www.cbs.nl/en-gb/onze-diensten/methods/definitions/weight-units-energy>

12) The data are available at Statistica “Natural gas consumption worldwide from 1970 to 2021,” Statistica: <https://www.statista.com/statistics/282717/global-natural-gas-consumption/>

13) See “Global Oil Infrastructure Tracker,” *Global Energy Monitor*, June 2022: <https://globalenergymonitor.org/projects/global-oil-infrastructure-tracker/>

14) The data for the EU and UK include 20 MW or over. See “Global Gas Plant Tracker,” *Global Energy Monitor*, July 2022: <https://globalenergymonitor.org/projects/global-gas-plant-tracker/>

15) Martin Placek, “Global oil tanker fleet 2012–2021,” Statistica, November 18, 2022: <https://www.statista.com/statistics/1326758/number-of-oil-tankers-worldwide/>

16) N. Sonnichsen, “Global fleet of LNG tankers 2010–2021,” Statistica, May 31, 2022: <https://www.statista.com/statistics/468412/global-lng-tanker-fleet/>

primary materials that human beings use to construct their sprawling built environments. The annual consumption of cement and concrete in 2021 stood at 4.3 billion metric tons and roughly 40 billion metric tons respectively.<sup>17)</sup> Thus humanity's annual fossil fuel consumption is almost 39% of the total mass of concrete used annually to build roads, bridges, buildings, and myriad other infrastructures across the planet.

The point is that the conventional energy sector is enormous and includes myriad infrastructures. Transformation of this energy sector is an unprecedentedly massive undertaking that will require decades. Even at the simplest summary of inputs, this transformation entails reducing the annual extraction and combustion of over 15 billion metric tons of fossil fuels while simultaneously building out clean energy infrastructure with millions of tons of critical minerals. Aside from biofuels, the clean energy that is to replace fossil fuels does not burn huge amounts of combustible fuel to produce heat, drive pistons, generate steam, and rotate turbines. Clean energy instead generates electricity, industrial heat and other forms of useful energy through nuclear fission and other processes within devices that often have a high material footprint. The core problem at present is that it remains easier to extract, refine and burn billions of tons of fossil fuels in structures built largely with steel and cement than it is to extract and refine many additional tons of critical minerals and deploy those critical minerals in spatially new energy systems centered on wind and solar. Moreover, the extraction and refining of the critical minerals, and the construction of the clean-energy economy, must also be done with fossil fuels.

## Clean Energy and Critical Minerals

Critical minerals are the focus of at least 14 national and regional (i. e., the EU) lists of commodities that are assessed as strategic to such key industries as clean energy, aerospace, microchips, health-care devices, computing, and national defense.<sup>18)</sup> The lists of critical minerals vary by jurisdiction and over time, but in general they include cobalt, graphite, rare earths, and about two dozen other elements on the periodic table. As of this writing, the

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17) Cement is of course the binding agent used to produce concrete. Concerning the consumption data, see "UNSUSTAINABLE: Concrete and cement," June 15, 2022: <https://2150-vc.medium.com/unsustainable-concrete-and-cement-d501d38c764d>

18) The critical minerals lists and assessments are summarized by Ana Elena Sancho Calvino in "What makes 'critical materials' critical?" Global Trade Alert Zeitgeist Briefing # 5, November 30, 2022: <https://www.globaltradealert.org/reports/102>

International Energy Agency's (IEA) 2021 report on *The Role of Critical Minerals in Clean Energy Transitions* remains the best available summary analysis of clean energy and critical mineral demand and supply.<sup>19)</sup> The IEA study recognizes that copper is a critical mineral, since there is no electrification without it, even though many country lists do not yet include copper. The IEA study reviews the supply and demand data for copper in addition to silicon, nickel, lithium, rare earths, and other critical minerals that are required for 16 clean-energy technologies. These technologies include wind power, solar power, nuclear power, and other options, together with electric vehicles (EVs) and other storage and network items. The IEA is one of the global community's strongest advocates of decarbonization and transitioning away from fossil fuels. But the IEA also bases its reporting and other work on empirical evidence, which indicates that ambitious and rapid scenarios of decarbonization imply very high levels of demand for critical minerals. The IEA's work on supply capacity for many critical minerals also suggests that meeting accelerated demand may be very difficult. We should also note that the IEA data are, if anything conservative. Their survey is focused on energy-related demand, and therefore does not include the potentially large critical mineral demand from advanced health care, communications, space technologies, defence systems, and other very mineral-intensive areas.<sup>20)</sup> Nor does it analyze the full slate of 30-odd critical minerals in Japanese, EU, US,<sup>21)</sup> Canadian, Australian, and other countries' current lists.<sup>22)</sup>

Figure 1 depicts the range of energy technologies – including hydrogen – that the IEA assessed and summarizes their dependence on select critical minerals. The relative degree of dependence is expressed in black, grey and white dots, respectively indicating high, medium and low reliance. The figure shows that EVs and battery storage are particularly

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19) *The Role of Critical Minerals in Clean Energy Transitions*, International Renewable Energy Agency, May 2021: <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>

20) A much broader survey of critical minerals and development can be found in Daniel M. Franks, et al., "Mineral security essential to achieving the Sustainable Development Goals," *Nature Sustainability*, October 10, 2022: <https://www.nature.com/articles/s41893-022-00967-9>

21) Note that as of February 2022, the US critical mineral list includes 50 minerals, as it separates the rare earth elements into individual items. See Jason Burton, "U.S. Geological Survey Releases 2022 List of Critical Minerals," Communications and Publishing, United States Geological Survey, February 22, 2022: <https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals>

22) The various countries' lists and their content can be found at Ana Elena Sancho Calvino, "What makes 'critical materials' critical?" Global Trade Alert Zeitgeist Briefing # 5, November 30, 2022: <https://www.globaltradealert.org/reports/102>

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

Source: IEA<sup>23)</sup>

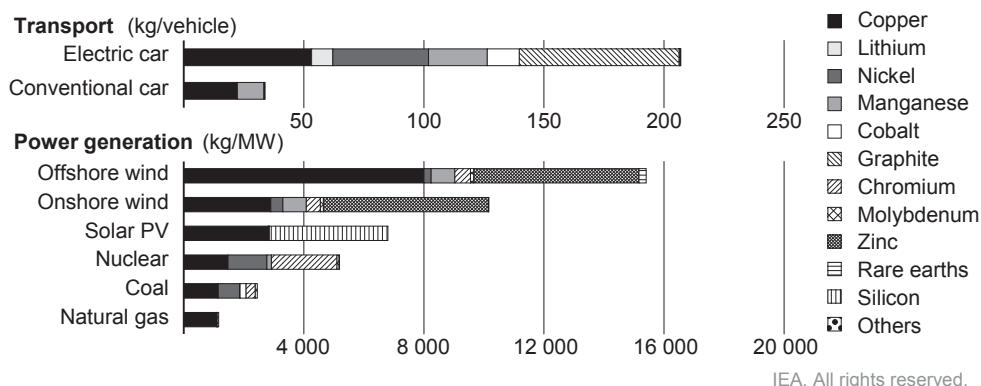
Figure 1 Critical Mineral Needs for Clean Energy Technologies

dependent on critical minerals. And among power generation technologies, intermittent wind and solar require much higher densities of critical minerals than such 24/7 baseload clean energy as hydro, geothermal and nuclear. Electricity networks – meaning the elements of transmission and distribution systems – also require large amounts of copper and other critical minerals. Spatially distributed wind and solar power thus have even higher “system costs” of critical minerals, since their dispersed power generation has to be networked with extra power lines, storage devices, and other assets.

### Critical Minerals, Electric Vehicles and Power Generation

A comparative quantification of critical mineral density for electric vehicles (EVs) and clean power generation is seen in **figure 2**. The figure’s top section (“Transport”) reveals that an average EV is over 5 times more material-intensive than a conventional, internal-combustion engine (ICE) car. The functionality of EVs requires far more copper and manganese than an ICE car, in addition to nickel, cobalt, rare earths and other critical minerals that are generally not used in ICE cars. The significance of the different per-vehicle dependence on critical minerals is due to the scale of the global car fleet, irrespective of trucks and other large vehicles that will also need to be decarbonized. In 2022, the total global fleet

23) *The Role of Critical Minerals in Clean Energy Transitions*, International Renewable Energy Agency, May 2021: <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>



Source: IEA<sup>24)</sup>

Figure 2 Minerals Used in Select Clean Energy Technologies

of ICE vehicles was about 1.2 billion passenger cars, whereas the global EV fleet had perhaps reached 27 million compared to 1 million in 2016.<sup>25)</sup> The electrification of passenger vehicles is certainly unfolding rapidly, but it has only just begun.

Though EVs sales are increasing apace, that is from a small number compared to the total global auto fleet, and it seems quite unlikely that EVs will replace the enormous scale of ICE vehicles. Even the initial rollout of EVs is causing unprecedented challenges in the supply of critical minerals. As of this writing, lithium prices were up 10-fold from the start of 2021, with nickel up 75% and cobalt more than double its average cost in 2020.<sup>26)</sup> Just as the sales of EVs took off, Bloomberg Intelligence warned in its Europe Autos 2023 Outlook “that escalating battery costs and battery demand could be the industry’s next bottleneck” and the IEA pointed out that by 2030 EV demand alone would need 50 additional lithium projects, 60 new nickel mines, and 17 cobalt projects. Industry observers openly expressed doubt that supplies could expand enough to meet soaring demand.<sup>27)</sup> And EV industry leader Tesla was

24) *The Role of Critical Minerals in Clean Energy Transitions*, International Renewable Energy Agency, May 2021: <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>

25) On vehicle fleets and EVs, see Colin McKerracher, “The World’s Electric Vehicle Fleet Will Soon Surpass 20 Million,” *Bloomberg News*, April 8, 2022: <https://www.bloomberg.com/news/articles/2022-04-08/plug-in-ev-fleet-will-soon-hit-a-20-million-milestone>

26) Harry Dempsey, “Electric car battery prices rise for first time in more than a decade,” *Financial Times*, December 6, 2022: <https://www.ft.com/content/f6c409d3-a29b-48f8-9f17-5586a1963d16>

27) “Cost of minerals vital for electric vehicle batteries soars,” *Electric Fleet News*, December 28, 2022: <https://www.fleetnews.co.uk/news/latest-fleet-news/electric-fleet-news/2022/12/28/cost-of-minerals-vital-for-electric-vehicle-batteries-soars>

compelled to accept a new lithium supply agreement based on floating costs adjusted for market prices, a striking change from its previous fixed-price contracts for long-term supply.<sup>28)</sup> These alarming changes occurred in the space of a year or so, overwhelming a powerful narrative that insisted there were no issues to be concerned about because recycling, substitution, and other strategies would alleviate risks of shortages.<sup>29)</sup>

Similar issues are evident in intermittent renewable energy. **Figure 2**'s lower section ("Power generation") demonstrates that clean power generation technologies have significantly higher material-density, expressed as kilograms/megawatt (kg/MW) of generation capacity. GHG-intensive natural gas and coal-fired generation require only moderate amounts of copper, nickel and other critical minerals for the combustion turbines and other infrastructure that compose their plant. But a conventional nuclear power plant requires more than double the critical minerals, per MW, of a coal plant and triple that of a natural gas generation asset, with an especially heavy reliance on chromium. In turn, solar and onshore wind generation both rely heavily on copper, followed by silicon for solar and zinc for onshore wind. Offshore wind is particularly dependent on copper and zinc plus rare earths. Moreover, the per-MW footprint of critical minerals balloons from a couple of metric tons for a natural gas plant to nearly 16 tons for offshore wind. Since intermittent wind and solar have considerably lower capacity factors than fossil-fuel and nuclear plant, their total volume of critical minerals required to produce a given amount of power is even higher than expressed in the figure.

The IEA data also suggest that small-scale distributed renewable energy systems – often hailed as key to community resilience and climate justice – need to be rethought in light of critical minerals. This is because the more distributed the renewable power generation and storage the higher the material-intensity. The IEA warns that "[d]istributed solar PV systems tend to have string inverters or microinverters, requiring about 40% more copper than utility-scale projects, which typically use central inverters. Other mineral intensities

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28) Yvonne Yue Li and Bloomberg, "The hits just keep coming for Tesla as it gets ready to pay more for the lithium it needs to make electric cars," *Fortune*, January 4, 2022: <https://fortune.com/2023/01/03/tesla-lithium-higher-prices-electric-vehicles/>

29) Cobalt was one material whose issues were thought to be ameliorated by substitution and other measures. But the evidence indicates rapidly expanded mining is essential. See Anqi Zeng, et al., "Battery technology and recycling alone will not save the electric mobility transition from future cobalt shortages," *Nature Communications*, 13, 1341, March 15, 2022: <https://www.nature.com/articles/s41467-022-29022-z>



are similar between utility-scale and distributed applications.”<sup>30)</sup> More recent work on power grids per se warns that “[r]esults show that the associated electrical grids require large quantities of metals: 27–81 Mt of copper cumulatively, followed by 20–67 Mt of steel and 11–31 Mt of aluminum. Electrical grids built for solar PV have the largest metal demand, followed by offshore and onshore wind. Power cables are the most metal-consuming electrical components compared to substations and transformers.”<sup>31)</sup> If the critical mineral issues threatening EVs expand to renewables, then the distributed renewable paradigm may need careful reconsideration and recognition of tradeoffs.

### Critical Minerals and Solar Power

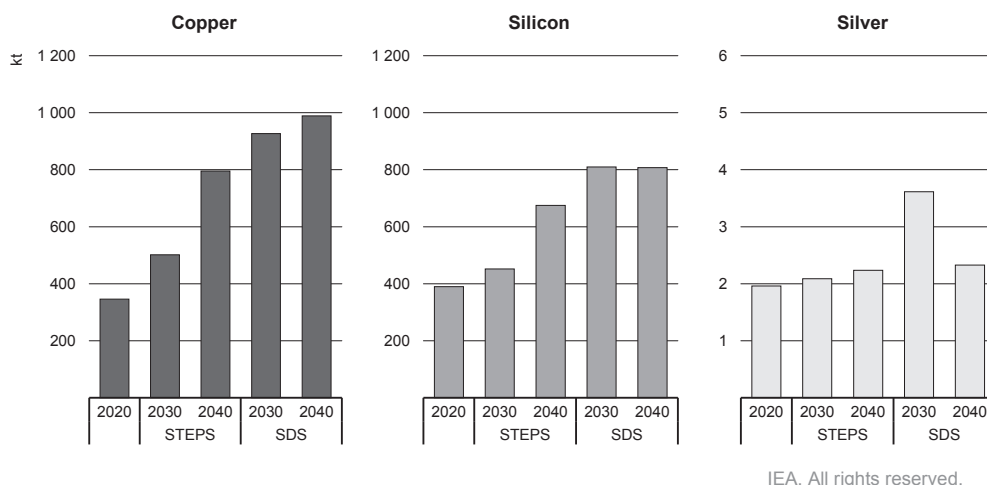
Solar power is perhaps the most prominent among the renewable options, and strongly advocated for by myriad interest groups. But it entails significant critical mineral costs. **Figure 3** presents detailed data on solar panels’ reliance on three key critical minerals between 2020 and 2040. It displays in kilotons (kt) the 2020 demand for copper, silicon and silver in global solar deployments, numbers that do not include 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 Celsius; 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 reliance on copper sees its demand nearly triple 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 in 2020 to over 800 kt in SDS 2030, and then levels off through technological change and recycling. And silver demand spikes from nearly 2 kt in 2020 to over 3.5 kt in the SDS 2030 scenario.

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30) See p. 56 *The Role of Critical Minerals in Clean Energy Transitions*, International Renewable Energy Agency, May 2021: <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>

31) Zhenyang Chen, et al. “Metal Requirements for Building Electrical Grid Systems of Global Wind Power and Utility-Scale Solar Photovoltaic until 2050,” *Environmental Science and Technology*, December 29, 2022: <https://pubs.acs.org/doi/10.1021/acs.est.2c06496>



Source: IEA <sup>32)</sup>

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

Though copper and silicon are usually the focus of attention concerning solar's requirement for critical minerals, silver is also problematic. In 2022, solar deployment globally was approximately 1 terawatt (TW), delivering about 5 % of global electricity demand. But the 2020 stock of solar already represented 12.7% of global silver production. And expert analyses already warn that even with reductions of silver use in solar, demand by 2030 could exceed 5 kt/yr, or about 21% of total global silver supply.<sup>33)</sup> And competing demand for silver includes EVs, 5 G telecommunications, and other advanced technology, so tradeoffs seem inevitable.<sup>34)</sup>

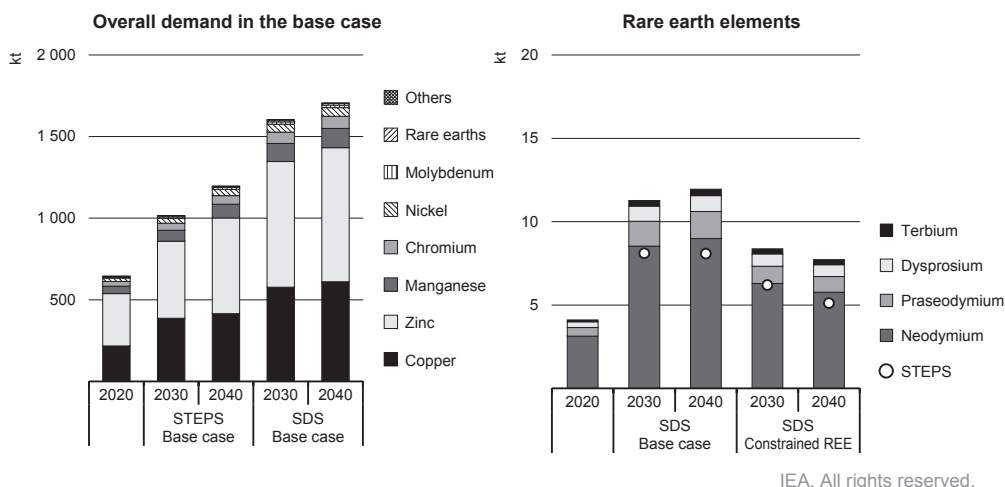
## Critical Minerals and Wind Power

Figure 4 outlines the critical minerals requirement for onshore and offshore wind

32) *The Role of Critical Minerals in Clean Energy Transitions*, International Renewable Energy Agency, May 2021: <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>

33) Brett Hallam, et al., "The silver learning curve for photovoltaics and projected silver demand for net-zero emissions by 2050," *Progress in Photovoltaics*, December 15, 2022: <https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3661>

34) Shane Lasley, "Silver evolves from money to techno metal," *Mining News North*, September 16, 2021: <https://www.miningnewsnorth.com/story/2021/09/16/critical-minerals-alliances/silver-evolves-from-money-to-techno-metal/6986.html>



Source: IEA <sup>35)</sup>

Figure 4 Mineral Demand for Wind by Scenario

power in 2020 and then out to 2040. The left-hand side of the figure shows that copper, zinc and other critical minerals demand nearly triples between 2020 and 2030 in an SDS scenario. The right-hand side of the figure outlines the wind-related rare earth element (REE) demand, estimated to more than double its 2020 levels in the SDS base case for both 2030 and 2040. The IEA does offer an SDS scenario wherein REE demand – ie, terbium, dysprosium, praseodymium, neodymium – is constrained by substitution, greater efficiency, and other measures. But we cannot be certain those will eventuate. And even if they do, those materials' role in making permanent magnets for wind turbines sees their demand double by 2030. And offshore wind is particularly dependent on copper, which is often included among the critical minerals (for example, in Canada's list). <sup>36)</sup>

## Critical Minerals and Other Renewables

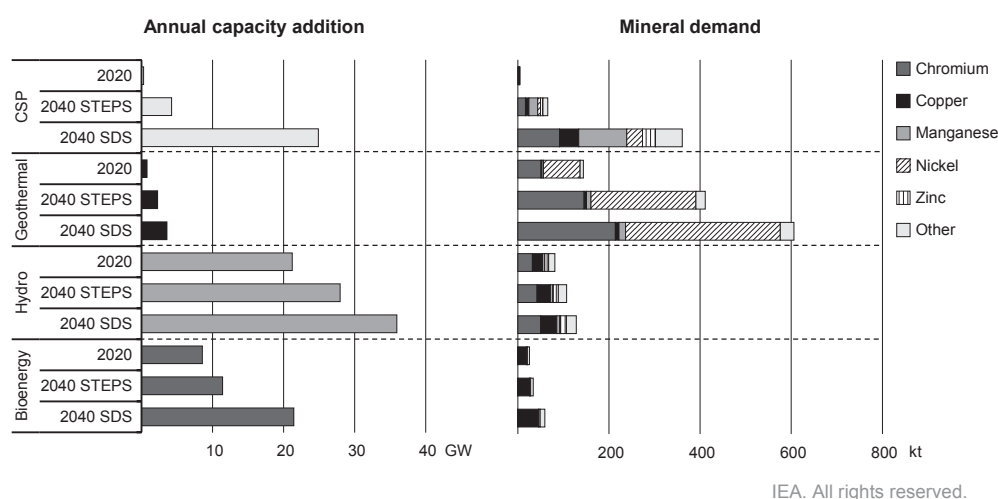
Solar and wind are the primary renewable technologies in the public debate on decar-

35) *The Role of Critical Minerals in Clean Energy Transitions*, International Renewable Energy Agency, May 2021: <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>

36) See Dieuwertje Schrivers, et al., "A review of methods and data to determine raw material criticality," *Resources, Conservation and Recycling*, Vol. 155, April 2020: <https://www.sciencedirect.com/science/article/pii/S0921344919305233>

bonization. But there are several other existing and potential renewable-energy technologies, and each has its own average profile of critical mineral demand. The left and right-hand sides of **figure 5** outline, respectively, the capacity additions and consequent critical minerals demand for four of them: concentrated solar power (CSP),<sup>37)</sup> geothermal, hydro, and bioenergy. Among these four, a nearly 25-fold capacity addition is expected from CSP by 2040 in an SDS scenario. That expansion of CSP implies a dramatic increase in critical minerals, rising from negligible amounts in 2020 to just under 400 kt by 2040. By contrast, geothermal power is not expected to contribute much new capacity, even in an accelerated SDS scenario. But geothermal power has a striking dependence on chromium and nickel per GW of additional capacity.

**Figure 5** reveals that hydro and bioenergy (including solid biofuels, biogas, incineration of municipal waste, and liquid biofuels) are the least material-intensive renewables.



IEA. All rights reserved.

Source: IEA<sup>38)</sup>

**Figure 5** Annual Capacity Addition and Mineral Demand from Other Renewable Technologies, by Scenario

37) Concentrated solar power (CSP) is generally characterized by concentric rings of mirrors that direct sunlight onto a central tower containing a thermal sink. The absorption of heat from the focused sunlight is then used to power steam turbines to generate electricity. Unlike conventional solar photovoltaic panels, CSP is capable of 24-hour operation, drawing on the stored heat in the central tower.

38) *The Role of Critical Minerals in Clean Energy Transitions*, International Renewable Energy Agency, May 2021: <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>

They also represent a lot of generation capacity and actual generation. In 2020, hydro alone represented 43% of total global renewable capacity and contributed about 58% (4,418 TWh) of total global renewable power generation of 7,660 TWh. Yet recently, hydro confronts challenges due to climate change and the need for flexibility. For its part, bioenergy represented 9.3% of total global renewable power generation in 2020. It is expected to double in capacity in the IEA'S 2040 SDS scenario. Bioenergy's critical minerals cost is minimal; but depending on the feedstock, the environmental cost is often significant because of reliance on food crops and land for growing the material input.<sup>39)</sup>

### Critical Minerals and Nuclear Power

Figure 6 summarizes the expected capacity additions and critical minerals demand from nuclear power for STEPS and SDS scenarios. It 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. The data for Japan assume restarts of idled capacity rather than new build. The IEA also suggest that the 2040 SDS scenario requires that average annual capacity additions double, especially in China. Even larger nuclear capacity additions are likely in China, India, and many European countries because public acceptance of nuclear power became generalized during 2022. The global energy crises that preceded the 2021 Russian invasion of Ukraine and then accelerated afterwards greatly shifted the public debate on nuclear.<sup>40)</sup> The material costs of projected nuclear capacity for 2030 and 2040 SDS scenarios are slightly more than 80 kt, mostly for chromium, copper and nickel. As we saw in figure 2, this material density per MW of generating capacity is far less than what is needed for solar and onshore or offshore wind. And nuclear capacity does not require the extensive power network (transmission, storage and other infrastructure) these intermittent renewables need to be integrated into the overall power system.

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39) A regularly updated summary analysis of bioenergy can be found in the various publications of the IEA Bioenergy Technology Collaboration Programme: <https://www.ieabioenergy.com>

40) In this regard, see the results of a 30-country poll conducted by the internationally recognized polling firm Ipsos and released on December 9, 2022. The poll indicates that support for nuclear power increased 7 % overall among the 30 countries, relative to 2021, and even higher in France (+10%), Germany (+15%), Spain (+13%), Italy (+17%), and the UK (+13%). The dramatic increases apparently reflect concerns over energy security and prices. See "Climate change: a growing skepticism," Ipsos, December 9, 2022: <https://www.ipsos.com/en-us/news-polls/obscop-2022>

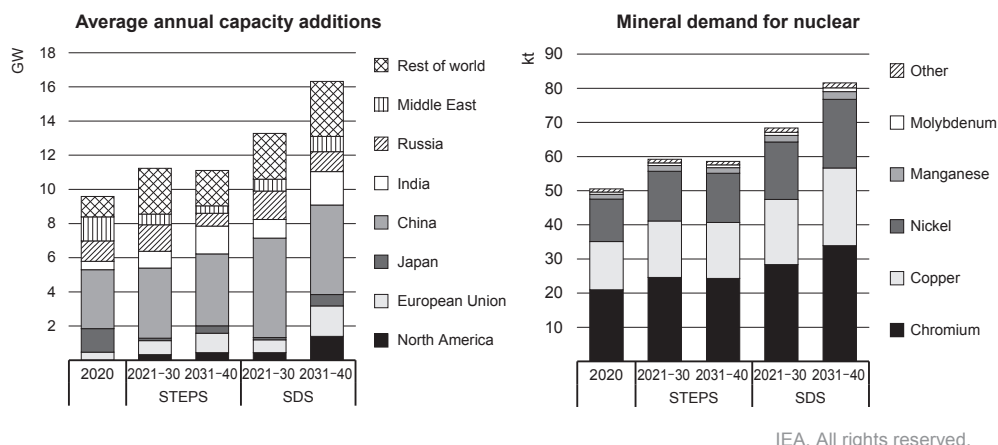


Figure 6 Average Annual Capacity Additions and Mineral Demand from Nuclear Power

## The Need for Unprecedented Volumes of Critical Minerals

We saw in the above that clean energy – and especially intermittent renewables – requires significantly higher volumes of critical minerals per unit of output. A rapid decarbonization led by EVs and variable renewables has indeed already led to massive demand for critical minerals. We have seen that this increasing demand has already led to price increases. In the IEA scenarios, even the moderate STEPS implies a doubling of solar deployment between 2019 and 2040, with corresponding increases in wind, electricity networks and electric vehicles. Under the more aggressive SDS scenario, solar capacity, wind capacity, and electricity networks triple between 2020 and 2040, while EVs increase 25 times to reach over 75 million new sales per year. In consequence, overall demand for the 30-odd critical minerals used in clean-energy technologies is expected to increase by six-fold or more.

Of course, the rate of increase in demand for any given critical mineral depends on which clean-energy elements are emphasized. But note that the SDS tripling of intermittent solar and wind by 2040 entails a massive increase in utility scale storage. To achieve this deployment, nickel demand for storage is projected to grow 140 times, cobalt by 70 times, and manganese by 58 times. Similarly, SDS by 2040 implies 42 times more lithium must be pro-

41) *The Role of Critical Minerals in Clean Energy Transitions*, International Renewable Energy Agency, May 2021: <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>

duced over the two decades between 2020 and 2040, followed by 25 times more graphite, 21 times more cobalt, 19 times more nickel, and 7 times more rare earths. These increased volumes are well beyond precedent in critical mineral mining.

And the IEA scenarios, like most others, are conservative and underestimate developing country demand. As Isabella Ramdoo, Deputy Director of the Intergovernmental Forum on Minerals, Mining and Sustainable Development, points out: “forecasts mainly assume the energy transition demand will be driven by advanced and emerging economies, currently in the driver’s seat for the clean energy technology revolution. However, 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. In any case, current forecasts are surely underestimated, as observed by the mounting pressure on the minerals market.”<sup>42)</sup> Absent very quick substitution for minerals, the rise in critical mineral costs will either mean that developing countries’ needs are sacrificed or that developed countries pursue more diversified means of decarbonization.

One common response to the above evidence is to assert that critical mineral needs are far less than fossil fuels. That is indeed true, but the mining and refining processes are vastly different, as are the geologic depositions. So it is not simply a matter of redeploying mining assets to extract millions of tons of critical minerals rather than billions of tons of fossil fuels.

Another common rebuttal is to pose a straw-man argument that suggest concern about critical minerals is an unfounded worry over total resources. But almost no one suggests the world confronts absolute resource scarcity at present, as critical minerals reserves are nowhere near geological exhaustion. Indeed, most of them have plentiful terrestrial reserves and resources,<sup>43)</sup> and many are abundant on or beneath the world ocean’s floor or dissolved within its waters. For example, the amount of uranium (a critical mineral in Canada’s list) dissolved in seawater is about 1,000 times that in terrestrial sites.<sup>44)</sup>

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42) See Isabella Ramdoo, “Is Future Supply of Critical Minerals Difficult to Predict?” Mexico Business News, November 4, 2022: <https://mexicobusiness.news/mining/news/future-supply-critical-minerals-difficult-predict>

43) Resources and reserves differ in the fact that the former is a general estimate of discovered and undiscovered deposits of a particular commodity, whereas reserves refer to known deposits that can be extracted economically.

44) Melike Benan Altay, et al., “Comparative Life Cycle Assessment of Uranium Recovery from Brine,” *Resources, Conservation and Recycling*, Volume 181, June 2022: <https://www.sciencedirect>.

Yet building the mining and refining capacity to extract critical minerals and render them useful as material inputs into production takes many years. And those steps are preceded by years of feasibility studies, environmental assessments, water and power infrastructure installation, and other steps. That lengthy lead time for bolstering upstream mining and refining supply – on average about 16 years for copper mining<sup>45)</sup> – contrasts sharply with the mere two years it takes to build a battery gigafactory at the downstream end of the supply chain. One result is a rapidly expanding gap between lithium supply and demand in the battery space, and thus the striking price increases noted earlier.

### Critical Minerals and Geopolitical and ESG Issues

A major geopolitical problem with critical minerals is their comparative geographical concentration of production, especially compared to fossil fuels and other important commodities. The largest producers of fossil fuels, including the U.S. and Saudi Arabia, hold relatively small market shares of oil and natural gas (coal is even more distributed) compared to the top producers of critical minerals. Indeed, the Democratic Republic of the Congo is the site of roughly 70% of cobalt production, while China extracts 60% or more of rare earths and graphite. The higher the concentration of critical minerals mining and refining, the greater the geopolitical risks for consumer countries. These risks include producer countries' increasing incentives to raise royalties – a reasonable strategy considering the value of the commodity – further increasing critical minerals prices and the decarbonization options they are needed for. Concentrated supply chains also exacerbate risks from natural disasters, the increasing role of organized crime in critical minerals,<sup>46)</sup> strikes and other industrial action, conflicts such as the Russian invasion of Ukraine, and related phenomena.

Compounding these problems is China's large presence in rare earths and many other critical minerals' mining and refining. China's dominance is due to decades of very smart industrial policy. And the country's dominance of many critical minerals supply chains may be quite durable in spite of the 2021–2022 uprush of policymaker concern in the EU, North

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com/science/article/abs/pii/S0921344922000854?via%3Dihub

45) Esmarie Iannucci, "Copper shortages to hamper net-zero targets – report," *Mining Weekly*, July 14, 2022: <https://www.miningweekly.com/article/copper-shortages-to-hamper-net-zero-targets---report-2022-07-14>

46) Marcena Hunter and Gideon Ofori-Peasah, "Organized crime threatens green minerals," *Global Initiative Against Transnational Organized Crime*, December 14, 2022: <https://globalinitiative.net/analysis/organized-crime-green-minerals-cop-27-climate-change/>



America, and elsewhere to reshore or at least diversify their supply chains. It will require many years and a lot of money to reshaped supply chains.

Though the oft-cited response to concentrated supply chains is to call for diversification, that is far easier said than done. Critical minerals mining is capital intensive, time-consuming, and environmentally disruptive. Moreover, mining firms are not yet incentivized to invest enough capital for critical mineral volumes to meet the IEA's SDS scenarios or even more ambitious decarbonization goals. These conundrums have long been highlighted by the IEA and other observers. Wood Mackenzie Senior Vice President and Vice Chair of Metals and Mining, Julian Kettle, warned of the gap between investment incentives and developed-economy policies on May 23, 2022: "Miners are constrained by investor reticence to sanction faster growth at the expense of dividends, long project lead times and rising above-ground risk. Policymakers are sending the wrong signals, claiming they are open for business and then constraining the development of mining projects that would deliver the metals required. They're not fully on-board on the need for a massive expansion of primary extraction."<sup>47)</sup> It is clear that policymakers do not grasp the scale of the crisis unfolding before their eyes, and hence are content to try and bridge conflicting public demands.

But critical mineral mining projects take place in a messy world of cyclical demand, high price volatility, often intense local opposition, and other sobering investment risks. Mining firms read all the IEA and other reports, and hence know quite well that 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 they cannot be certain of that estimate, and they are not equipped to act alone on it even if they believed it completely. The miners do not, for example, dominate the institutions that grant licenses to undertake projects. And policymakers in the developed countries sign agreements to foster more action on supply, but then seem more inclined to privilege anti-mining interest groups.<sup>48)</sup> The upshot of the above is that it is unlikely we will see significant reshoring and other diversification of mining and refining over the next decade. Given the accelerating demand, that limited capacity for new supply is not a sustainable scenario.

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47) Julian Kettle, "Could Big Energy and miners join forces to deliver a faster transition? Wood Mackenzie, May 23, 2022: <https://www.woodmac.com/news/opinion/could-big-energy-and-miners-join-forces-to-deliver-a-faster-transition/>

48) Karoline Schaps, "Copper shortfall's 'dramatic impact' on energy transition drives search for answers. International Bar Association," December 15, 2022: <https://www.ibanet.org/Copper-shortfall-dramatic-impact-on-energy-transition-drives-search-for-answers>

An additional serious problem is declining critical minerals ore grades and their impact on mining's financial and environmental costs. One example is the 30% decline in copper ore-grades in Chile from the mid-2000s to 2020. These declining ore grades mean that more ore must be extracted and processed to produce a unit quantity of copper and other critical minerals. The additional mining and refining raise the energy cost of a unit quantity of critical minerals. Those processes also require increased use of water often in water-stressed areas, larger volumes of waste rock and mine tailings, and higher GHG emissions. Climate impacts are generally worsening water stress in many mining areas, such as South America and South Africa, so increased mining of depleting ore grades risks exacerbating water stress in the absence of costly countermeasures such as water recycling and desalinization.

A further problem is mine tailings, or the waste left after refining separates the metal ore from the mined rock. Mine tailing are a slurry of particles mixed with water, and a voluminous and polluting issue at the mining site. The tailings are generally stored in settling ponds, and the global total of these ponds is a staggering 282.5 billion metric tons occupying a volume of 217.3 km<sup>3</sup>. Copper is responsible for about 46% of global mine tailings, with significant amounts also from other critical minerals.<sup>49)</sup> The mining and refining of rare earths also produce significant quantities of radioactive materials and other impurities.<sup>50)</sup> So it is no surprise at all that decarbonization advocates in the developed world prefer to talk about reviving communities with solar panels and EVs rather than the mining needed to build them.

### Limited Prospects for Critical Mineral Recycling and Substitution

Critical minerals extraction is generally unwelcome, and therefore most work on energy transitions stresses recycling in "circular economy" strategies. These strategies aim to recycle or repurpose and otherwise reduce the need for newly mined copper, cobalt, rare earths and other metals and minerals. Substitution strategies complement this approach, by devising new materials to replace the role of supply-constrained minerals used in batteries, solar panels, and other devices. But the IEA analysis does not expect recycling or substitution to play much of a role for at least a couple of decades. And this forecast is consistent

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49) Nicholas LePan, "Visualizing the Size of Mine Tailings," Visual Capitalist, May 15, 2022: <https://elements.visualcapitalist.com/visualizing-the-size-of-mine-tailings/>

50) Jingjing Bai, et al., "Evaluation of resource and environmental carrying capacity in rare earth mining areas in China," *Nature Scientific Reports*, 6105, April 12, 2022: <https://www.nature.com/articles/s41598-022-10105-2>

with many other sober assessments of critical minerals issues.

One key reason for the limited prospects of circularity and substitution is that the world has only just begun to diffuse the requisite stock of EVs, intermittent renewables, power systems, and related critical minerals – intensive infrastructure. Recycling is not a large input when there is only a small amount of stuff to disassemble and meld down. New material flow from recycling only gains serious traction in supply scenarios after a very large infrastructure stock has both been deployed and then used for a decade or however many years are the specific asset’s average useful life cycle.

Adding to the problem is that many of the devices currently being deployed are not built for recycling. Designers do not prioritize recycling over functionality or appearance of the product. And a devices often consist of alloys and other critical minerals combinations that are difficult to recover.<sup>51)</sup> Thus the IEA suggests that by 2030, recycled battery materials are at best a source of 1 % of demand, and provide only about 8 % of demand as late as 2040 critical minerals.

To reiterate, 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. Once that huge stock is in place and portions of it have reached the end of their useful life, then one can expect some appreciable level of critical minerals flows from recycling. So while stronger policies on recycling and substitution need to be adopted, they are not likely to bear fruit for decades. And they need to be coupled with device design that prioritizes recyclability over appearance and other factors.

## Conclusions

We have seen that the GHG-intensive fossil fuel economy is enormous, composed of 15.5 billion metric tons of fuels in addition to a vast deployment of pipelines, refineries, shipping stock, and uncountable other assets. The aim to decarbonize energy is therefore an unprecedentedly huge project that should not be obscured by simplistic claims that only political will is lacking.<sup>52)</sup> Abundant and cost-effective critical minerals supply is essential to building out the massive clean energy infrastructure needed for achieving decarbonization.

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51) T. E. Graedel, et al., “Alloy information helps prioritize material criticality lists,” *Nature Communications*, 13, 150, January 10, 2022: <https://www.nature.com/articles/s41467-021-27829-w>

52) Alejandro de la Garza, “We Have the Technology to Solve Climate Change. What We Need Is Political Will,” *Time*, April 7, 2022: <https://time.com/6165094/ipcc-climate-action-political-will/>

Like many other recent studies of critical minerals, the IEA's analysis emphasizes the role of comprehensive public policy, including not just new mining but also recycling, substitution, and innovation that helps increase the efficient use of critical minerals.

Aggressive and coordinated public policy is essential for securing abundant supplies of critical minerals for decarbonization at acceptable costs and so as not to compel sacrifices in health, education, and other areas. Countries also need to work together in fostering supply stability via clear policy goals that reduce the risks of critical minerals price volatility and other impediments to expanded mining and processing. But these kinds of initiatives are not yet in place, and the public debate has yet to apprehend the risks. The world's top experts on critical minerals are therefore very concerned: "Shifting to a clean energy economy will require a decades-long investment in technologies such as solar, wind, geothermal, nuclear, and batteries. All this infrastructure will require massive quantities of critical minerals... Over the last 5,000 years, the human race has mined 700 million tons of copper. That is roughly as much as will be needed over the next 22 years to meet global energy transition targets. This level of supply production does not yet exist. New mines will have to be dug, and processing and refining industrial complexes will need to be built – both exceedingly difficult to do with existing permitting rules."<sup>53)</sup> Government dysfunction in the developed world suggests that these imperatives will not be addressed until there is an enormous crisis on par with the COVID-19 pandemic or the global energy-price shocks of 2021-2022.

In consequence, price increases in variable renewables and EVs seem certain to escalate and become protracted as opposed to transitory. And for the myriad reasons discussed above, higher critical minerals prices will not quickly lead to a lot of new mining. 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."<sup>54)</sup> There is virtually no short to medium-term prospect of large-scale substitution, recycling and other silver-bullet countermeasures to the critical mineral crisis. So strategic

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53) Morgan Bazilian and Gregory Brew, "The Missing Minerals," *Foreign Affairs*, January 6, 2022: <https://www.foreignaffairs.com/united-states/missing-minerals-clean-energy-supply-chains>

54) Nelson Bennett, "Canada's minerals extraction in situation critical," *Mining*, May 24, 2022: <https://www.mining.com/canadas-minerals-extraction-in-situation-critical/>

prioritizing of the use of supply-constrained critical minerals will almost certainly become necessary, such as by fewer and smaller EVs and more compact urban design. At present, this kind of thinking is not evident among the debates over decarbonization. The result of the inattention is thus likely to be a longer and more costly decarbonization.