The clean energy transition is essentially a shift from fossil fuels, including coal, natural gas, and petroleum, to nonfuel mineral commodities, such as tellurium, lithium, and rare earths. That is because clean energy technologies like solar panels, wind turbines, electric vehicles, and electric grid energy storage systems require significant quantities of these and other nonfuel mineral commodities—but it is, of course, much more than that. The clean energy transition is about trade and supply chains; manufacturing and jobs; resource nationalism and great power competition. It is also about the environment and community relations; economic development and the circular economy; emerging technologies and intellectual property. As we race toward the middle of the 21st century, one would be hard pressed to identify a topic that is at the nexus of more consequential issues than this one.

Consider that climate change—arguably the “biggest threat modern humans have ever faced” (United Nations Security Council 2023)—and mineral commodity supply chains are linked in at least three distinct ways. First, mineral commodities are essential to clean energy generation, transmission, and storage technologies. Second, the production of mineral commodities requires notable quantities of energy during mining, beneficiation, smelting, and refining operations, currently resulting in greenhouse gas (GHG) emissions that cause climate change. Third, the effects of climate change can impact mineral commodity supply chains by disrupting mining and processing infrastructure and operations, affecting water availability and weather patterns that may be essential to certain operations and regional watersheds, changing access to supply chains and disrupting trade routes, impacting worker health and safety, affecting ecosystems, and increasing conflict with local communities. Although distinct, the linkages between climate change and mineral commodity supply chains are also interdependent. For example, increasing demand for clean energy technologies (to offset the demand for fossil fuels that cause climate change) will result in increased demand for mineral commodities, the production of which may release additional GHG emissions that would increase the impacts of climate change and may, in turn, limit access to the necessary mineral resources. This Perspective article explores these linkages, discusses some of their interconnections, and highlights the importance of geometallurgy (the practice of combining geology or geostatistics with extractive metallurgy to design a spatially or geologically based predictive model for mineral processing plants) and systems thinking to tackle the potential positive feedback loops that could jeopardize the technological changes necessary to counter climate change.

As demand for clean energy technologies increases so, too, will demand for mineral commodities. For example, in addition to requiring cobalt, graphite, lithium, nickel, and manganese for certain lithium-ion batteries, electric vehicles (EVs) also require more copper and rare earth permanent magnets than their internal combustion engine (ICE) counterparts (International Energy Agency 2022). While demand for EVs and other clean energy technologies is expected to increase markedly in the coming decades, the specific technology or technologies that will become dominant is highly uncertain. There are, for example, several different lithium-ion battery cathode compositions including lithium nickel–manganese–cobalt oxide (NMC, at different proportions of nickel to manganese to cobalt), lithium nickel–cobalt–aluminum (NCA), lithium manganese oxide (LMO), and lithium iron phosphate (LFP). The different lithium-ion battery chemistries have different strengths and weaknesses regarding important aspects of functionality including lifespan, power and energy densities, safety, and cost. This uncertainty in technological choices and adoption rates translates into uncertainty for mineral commodity demand, as different technologies require different quantities and varieties of mineral commodities.

Certain lithium-ion battery cathode chemistries require relatively large quantities of cobalt (e.g., NCM 111, with equal proportions of nickel, cobalt, and manganese), some require considerably less cobalt but more nickel (e.g., NMC 811), while others do not require cobalt or nickel at all (e.g., LFP and LMO). Similarly, different solar PV technologies require different byproduct mineral commodities (e.g., silver for crystalline silicon versus cadmium and tellurium for cadmium telluride solar photovoltaics). Demand for mineral commodities will thus depend on not only the growth in the demand for solar PV, but also on the individual technologies that are adopted and their material intensities (Nassar et al. 2016). Mineral commodities will also be increasingly needed in various applications that may be less obviously identified as “clean” energy technologies, but will be needed for the reduction of energy use and related GHG emissions nonetheless. For example, the continuing trend toward the light-weighting of vehicles and aircraft may require the use of light-weight nonferrous alloys (e.g., aluminum–lithium alloys) and high-strength, low-alloy steels that require elements like niobium and vanadium. Conversely, the shift to clean energy technologies may decrease demand for some mineral commodities. Approximately 41% of platinum, 83% of palladium, and 89% of rhodium gross global demand in 2022 were in automotive catalytic converters for the reduction of tailpipe emissions of ICE vehicles (Bloxham et al. 2022)—demand that will not be needed for EVs. Additionally, some platinum-group metal demand is for catalysts used in petroleum refining, which may also diminish with the reduced demand for gasoline and diesel. This shift may “free up” some platinum-group metal supplies to be used in other applications, such as the production of “green” hydrogen via proton exchange membrane fuel cells and electrolyzer technology (Moreira et al. 2022).

As demand for certain mineral commodities increases, it is not clear that supply from primary or secondary (i.e., end-of-life or post-use recycling) sources can keep pace. Some analyses in the literature suggest that there is significant potential to increase the recovery of some byproduct mineral commodities, such as gallium, germanium, indium, and tellurium, which have historically not been recovered at high rates (Licht et al. 2015; Frenzel et al. 2016a, 2016b, 2017; Nassar et al. 2022a). There is an obvious need for the geosciences, and particularly geometallurgy, to help increase the knowledge necessary to determine if these potentials can actually be realized.

Most analyses in the literature (e.g., Eshkaki and Graedel 2013; Nassar et al. 2016; Moreira et al. 2022; International Energy Agency 2022), however, focus on developing demand forecasts or scenarios, with few examining demand and supply concurrently. The resultant picture is often one in which demand projections greatly surpass those of current supply (or current supply plus any additional supply from announced projects). In reality, without sufficient supply from primary and secondary sources, demand will not be fulfilled as projected, and prices will increase, leaving some to find substitute materials or other means of fulfilling that need. In anticipation of difficulties in securing cobalt supplies, some vehicle manufacturers have already begun shifting away from high-cobalt to low-cobalt and cobalt-free battery cathode chemistries (e.g., LFP) (Blois 2023). Higher-level (e.g., systems-level) substitution may also occur (or be encouraged via various policies) to offset some of the demand. Increased mass transit and designing urban areas for alternative and more efficient modes of mobility can, for example, offset some of the demand for new personal vehicles (Riofrancos et al. 2023).

Pressure to increase supply, as signaled through higher market prices, will likely result in mineral projects coming online that would have previously been considered uneconomic. Some of the previously uneconomic projects may have simply had relatively low ore grades. This has important implications as mining and processing ores with lower grades generally translates to greater volumes of waste (Nassar et al. 2022b), greater energy usage, and more GHG emissions (Norgate et al. 2010; Calvo et al. 2016). While it is recognized that large amounts of energy and GHG emissions are associated with major metals such as iron...
and steel (International Energy Agency 2020), relatively little information is available for many other mineral commodities. Some life cycle energy and GHG emissions data are available and updated regularly by mineral industry associations (e.g., International Aluminium Institute 2023). Most of the data in the life cycle inventory and related literature (e.g., Nuss and Eckelman 2014) are, however, not regularly updated and commonly cover only one or two “typical” operations. The degree of variability in energy usage and GHG emissions between operations is thus generally not known. Similarly, while there have been detailed asset- or process-based analyses for specific mineral commodities (see recent work on lithium-ion battery materials by Benchmark Minerals Intelligence (2023†) and the assessment of several commodities by Skarn Associates (2022†)), such efforts are typically limited in scope and commodity coverage. Having comprehensive asset-level information that is updated regularly can help in not only understanding the variability in the data, but also provides a strong foundation for understanding the key drivers of that variability between operations. This would thus provide essential information to understanding the energy use and GHG emissions of current mineral commodity supplies and the factors that may affect them in the future, thereby allowing companies and governments to make more informed decisions and policies.

Reducing GHG emissions of mining and processing operations will likely involve increasing the share of clean energy technologies that supply their electricity (which will increase demand for certain mineral commodities), as well as other efforts that seek to reduce or eliminate GHG emissions from the processes themselves. An example of the latter is the joint venture formed between Alcoa and Rio Tinto, Elysis, which in 2018, announced the development of a novel aluminum smelting process that does not directly release GHG emissions (Elysis 2023†). Again, geometallurgy can play a key role in understanding what might be possible with respect to reducing the amount of energy and GHG emissions in other mining and mineral processing operations. End-of-life recycling can also help reduce GHG emissions by utilizing less energy and emitting less GHGs than the processes used for new materials, and by offsetting the demand for additional material that would otherwise be required. There are, of course, technical, logistical, and economic challenges to recycling of mineral commodities (Reuter et al. 2013). However, end-of-life recycling’s contribution to the reduction of energy use and associated GHG emissions (and to reducing demand for new materials) will be comparatively small (at least to start) simply because it cannot keep pace with the rapidly growing demand for clean energy technologies. That is not to say that it will not be important or should not be encouraged; it is simply to state that recycling alone cannot be a solution if demand continues to grow.

Without significant abatement, climate change will likely impact the availability of (and/or accessibility to) mineral commodities in several ways including disruption of operations and related infrastructure due to increases in the frequency of severe weather events, changes in weather and precipitation patterns, and sea level rise; disruption of supply chains and trading routes; and impacts to community relations and worker health and safety (Nelson and Schuchard 2011). Consider lithium minerals, which will be required in lithium-ion batteries regardless of cathode composition. Lithium minerals are recovered from both hard rock (e.g., spodumene), as well as brine operations. Brine operations rely on solar irradiation and wind to concentrate the lithium. This evaporitic process is thus strongly dependent on climatic and weather conditions, in particular solar irradiation, rain levels, and wind strength (Flexer et al. 2018). There are other ways in which climate change may impact mineral supply chains. For example, hotter and drier conditions may lead to increased wildfires that may threaten facility operability; heavy rains may increase erosion that may cause slope instability at open cast mines; and reduced water availability may curtail operations and exacerbate strains with nearby communities, especially in water stressed areas (Nelson and Schuchard 2011; Northery et al. 2017; Delevingne et al. 2020). At the very least, supply chain disruptions will increase costs of materials or cause delays, which will likely translate into higher prices for consumers that, without intervention, would reduce demand for the clean energy technologies. Many of these and other effects and feedback mechanisms that climate change may have on mineral supply chains need to be examined systematically, especially when considering the fact that the production of most mineral commodities is highly concentrated (geopolitically and spatially) (Schnebele et al. 2019; Nassar et al. 2020) and that most mineral commodities are co-produced (Nassar et al. 2015).

It likely comes as no surprise that our decisions and collective actions over the coming years and decades regarding how we produce and store our energy, transport ourselves and our goods, grow our food, and build our cities will have profound implications for both human and Earth systems. What might be surprising to some is that nonfuel mineral resources and their supply chains might be at the center of it all. Will the transition to clean energy simply shift our dependency from fuel minerals to nonfuel minerals and recast the familiar problems and pitfalls of the past century? Or, will we avoid these problems, break the undesirable feedback loops, and usher in a genuinely new era of sustainable energy? The answer will depend, at least in part, on our ability to provide and successfully communicate the best and most timely science that we have available.

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As chief of the Minerals Intelligence Research Section at the U.S. Geological Survey, Dr. Nedal Nassar and his research team quantify the global stocks and flows of nonfuel mineral commodities at each stage of their life cycle, analyze trends and examine concerns regarding foreign mineral dependencies, develop supply and demand scenarios, and assess the mineral commodity supply risk to the U.S. economy and national security. Dr. Nassar received his PhD from Yale University (USA) where he worked on the development and application of a methodology for assessing critical minerals. He has continued that work as a leading member of the U.S. National Science and Technology Council’s Critical Minerals Subcommittee. He also serves as co-chair of the Council of Senior Science Advisors at the U.S. Geological Survey and has been on the advisory board of various international research projects. In 2019, he was awarded the Presidential Early Career Award for Scientists and Engineers—the highest honor bestowed by the U.S. Government to outstanding scientists and engineers who are beginning their independent research careers. His research has been published in high-profile journals and highlighted in major media outlets. He has also been called upon to testify before committees of the U.S. Senate and House of Representatives, brief senior government officials, and invited to give keynote addresses and present his research at significant venues including The National Academies, the European Commission, and the World Bank. Previously, Dr. Nassar worked as a consultant and as a process development engineer in the semiconductors and data storage industries where he was the recipient of three trade secrets. He also holds a bachelor’s degree in chemical engineering from the University of Minnesota (USA), an MBA in sustainable global enterprise from Cornell University (USA), as well as two master’s degrees from Yale University.
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