Mining for net zero: The impossible task

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Abstract

If current predictions of anthropogenically induced climate change are accurate, and they are becoming more robust and prescient with time, the world must transition away from fossil fuels and embrace transportation, energy generation, and energy storage from renewables so that future generations are not in peril. More than 190 countries have each signed the Paris Agreement, which has as its goal a reduction of global greenhouse gas emissions to limit the global temperature increase in this century to 2°C while pursuing efforts to limit the increase even further to 1.5°C. Additionally, more than 70 countries, including the biggest polluters, have set a net-zero greenhouse gas emissions target, which covers about 76% of global emissions — a commendable and laudable goal. However, a number of fundamental challenges make achieving this goal difficult, perhaps impossible. One such challenge is the lack of a broad appreciation that there needs to be much more mining of metals and minerals, in excess of already mining more than at any other time in prior human history. For example, one estimate is that there needs to be as much copper mined over the next 20–25 years as has been mined to date. Many countries have become aware of the need for access to "critical minerals" for futureproofing, but they appear to be unaware of the fundamental issues that will hamper that access. This is a fast-moving issue. Some of the specific details raised here will become less relevant, and new ones will appear. However, the core issues raised, of the need for a more positive public perception of mining, of the need for more mining, and of the need for far more skilled talent, will not change.

Introduction

The forecast of threats from anthropogenically induced climate change are well documented and cross-scrutinized (e.g., IPCC, 2022). These threats are detailed in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2022), particularly the Working Group II contribution that was released 28 February 2022. The issues facing us are complex and diverse. Besides the obvious ones, there are dissimilar issues in the public eye such as the huge carbon footprint of the semiconductor industry (Belton, 2021), the climate impact from eating meat (Neufeld, 2020), the long permitting times for solar and wind (e.g., in the European Union [Fox, 2022]), the subsidies of $11 million[4] per minute that the International Monetary Fund contends the fossil fuel industry reportedly receives (Carrington, 2021), and reports that Exxon and Shell grappled with climate change issues more than two decades ago (Waldman, 2018; Supran et al., 2023). Here, I focus solely on a geophysical perspective, which is broad in itself.

The core themes of this paper are (1) the lack of appreciation, among politicians, the public, and many geoscientists, of the need for far more mining, and far more mining than ever before in human history, and (2) the worrying decline in enrollments into the earth sciences, especially into exploration geophysics, at universities worldwide.

The world has, in principle, recognized the scale of the issue, and 196 parties at the UN Climate Change Conference in Paris signed a legally binding international treaty on climate change, the Paris Agreement, on 12 December 2015. The agreement entered into force on 4 November 2016. The overarching goal of the Paris Agreement is to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels." Unfortunately, the Intergovernmental Panel on Climate Change's synthesis of its mammoth Sixth Assessment Report, released 20 March 2023, concludes that it is likely that that limit will not be met, and keeping below 2°C this century will be challenging (IPCC, 2023).

We currently are emitting some 33.9 Gt of total CO_2 into our atmosphere (IEA, 2021). Of that total, some 63% is from energy generation and transportation (see Figure 12 from IEA, 2020). Left unchecked, or even worse enhanced, greenhouse gas emissions will lead to rapid, unprecedented temperature increases of more than 5°C by 2100 (Riahi et al., 2017; IPCC, 2022). To combat this bleak outcome, more than 70 countries, including all G7 nations and the biggest polluters (the European Union, the United States, and China), have set targets to achieve net-zero greenhouse gas emissions, most by 2050 (United Nations, n.d.). In 2021, the International Energy Agency laid out a road map for achieving net zero by 2050 (IEA, 2021). Some governments have enshrined this laudable and aspirational goal into law (Sweden, the United Kingdom, France, New Zealand, Denmark, and Hungary), and others have legislation pending (Canada, South Korea, and the European Union). Some countries also have accelerated time frames for achieving net zero (Uruguay by 2030; Finland by 2035; Austria and Ireland by 2040; Germany and Sweden by 2045). An updated list of countries and their commitments can be found at: https://eciu.net/netzerotracker.

Various scenarios and narratives for addressing the climate crisis have been proffered, with the most comprehensive being the Shared Socioeconomic Pathways (SSPs) summarized and discussed by Riahi et al. (2017). The most optimistic of these is "SSP1 Sustainability — Taking the Green Road," which has low challenges to mitigation but high challenges to adaptation and which requires us to make significant changes to our way of life.

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[4] Dollar amounts throughout are in U.S. dollars.

The worst case is "SSP5 Fossil-fueled Development — Taking the Highway," which has high challenges to mitigation and low challenges to adaptation — basically we carry on as we are, ignoring the climate crisis.

The International Energy Agency (IEA) distils down to two basic scenarios (IEA, 2022). Their Sustainable Development Scenario (SDS) is in line with the Paris Agreement and relies on most countries and companies hitting their announced net-zero emissions targets by 2050 and all countries by 2070. The other IEA scenario is the Stated Policies Scenario (STEPS), which takes into account the current policy measures and plans of national governments. STEPS will result in falling far short of the world's sustainability goals.

The modeled, projected global CO_2 emissions for the five SSPs and other narratives for the rest of the century have been derived by Hausfather (2019) and are shown in Figure 1, together with projections for some IPCC Representative Concentration Pathways. The 2013 IPCC Fifth Assessment Report (AR5) featured climate models from CMIP5 (Coupled Model Intercomparison Projects, version 5), while the 2021 IPCC Sixth Assessment Report (AR6) featured new state-of-the-art CMIP6 models.

Except for the completely irrational SSP5, what all other narratives have in common is that we must pivot and transition from fossil fuels for energy generation, energy storage, and transportation to various renewables — wind, solar, geothermal, hydropower, ocean power, green hydrogen, etc. What all of these renewables have in common is that they require huge amounts of metals and minerals, particularly critical minerals, to be mined over the next 30 years, and for these metals and minerals to become part of a circular economy; there is no point in adding more lithium or rare earth elements (REEs) to the economy with it being only for one-time use. The challenge of the latter point is discussed in Jowitt et al. (2018). Note also that the circular economy is not itself 100% efficient: there are losses with life cycle of metals and minerals in circulation. These range from less than a year for scandium, gallium, germanium, selenium, indium, and tellurium, to 4 years for cobalt, 7 years for lithium, 45 years for copper, and 60 years for nickel (Charpentier Poncelet et al., 2022). Although the latter two are "long," they are within this century and imply even more mining to fill their life cycle deficit.

Renewables are becoming much less expensive than fossil fuels for energy generation. The cost of solar photovoltaics decreased from \$359/MWh in 2009 to \$37/MWh in 2020, with the result that, using a levelized cost of energy analysis, wind and solar are now far less expensive than gas, nuclear, and coal for energy generation (Lazard, 2021). A recent paper by Way et al. (2022) analyzes the cost of delaying adoption of rapidly decarbonizing the global energy system. The difference between what Way et al. refer to as a "fast transition," which is achieving net zero by 2050, and "no transition" (essentially SSP5) is estimated to be approximately \$12 trillion. So, not only are there solid societal and scientific justifications for moving to renewables, there are strong financial incentives.

As I hope to show in this paper, to enable a fast transition and to meet net zero by 2050 we must have a commensurate acceleration in our extraction of necessary critical minerals. This will require an immediate pivoting of attention by a significant number of (younger) exploration geophysicists to mineral exploration and significantly increased enrollment numbers in exploration geophysics at our universities.

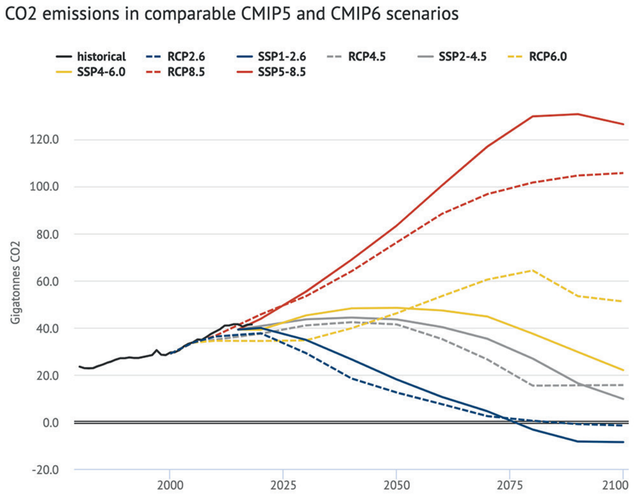

Figure 1. Global CO_2 emissions given various narratives. From Hausfather (2019).

The extent of the demand growth for the minerals and metals needed for the energy transition is overwhelming. The IEA projects that by 2040 we will need 42 times the lithium we produced in 2020, 25 times as much graphite, 21 times as much cobalt, 19 times as much nickel, 8 times as much manganese, 7 times as much REEs, 2.9 times as much molybdenum, 2.7 times as much copper, and 2.3 times as much silicon under its SDS (IEA, 2022). The far weaker STEPS, a scenario that is based on current national policies and that will fail to keep global temperatures below sustainable limits, will nevertheless still require 13 times as much lithium, 8 times as much graphite, 6 times as much cobalt, 6 times as much nickel, 3 times as much manganese, 3 times as much REEs, 2 times as much molybdenum, 1.7 times as much copper, and 1.8 times as much silicon (IEA, 2022).

Global mining exploration budgets have increased since a low in 2016. In 2021, the worldwide budget for nonferrous mineral exploration amounted to \$11.24 billion, which was a 35% increase over 2020 (Ferguson and Murphy, 2022). This is still significantly lower than the record levels seen in 2012 when the global exploration budget reached \$20.53 billion. However, the most targeted commodity was gold, accounting for more than half (55%) of exploration budgets. Gold does have a minor role to play in the energy transition, but, more importantly, copper accounted for the next highest percentage of exploration budgets at 21%. Silver (6%), nickel (4%), and lead-zinc (4%) followed, with the remaining 11% for all other minerals and metals, including potash and phosphates. Far larger budgets for exploration of critical minerals will be required if we are to achieve net zero by 2050.

This overview paper covers broad aspects related to mining in general. It highlights that the two biggest obstacles are (1) the poor public perception of mining, and (2) the diminishing numbers of students who are entering the earth sciences at university level. Both of these obstacles are related to a lack of broad appreciation of the magnitude of the problem — that there needs to be much more mining of metals and minerals compared to current levels if we are to continue humankind development without serious impediments and consequences.

However, mining and processing must use renewables themselves as well, as there is a huge carbon cost to produce the metals needed for the energy transition. Extraction and processing require a great deal of electricity. Some companies are already addressing this. BHP in particular has policies and actions in place to use energy from renewables at some of their mines (BHP, n.d.). The largest copper mine in the world, BHP's Escondida, is already using 100% renewables. Boliden also has expressed its commitment to low-carbon copper mining (Boliden, n.d.).

I have tried to present the most current projections and numbers possible throughout this paper for supply gaps. The issues are evolving rapidly, and many of the projections and numbers presented here are constantly being revised, in most cases upward. There also may be revolutionary developments that ease the transition, such as in battery chemistry so that we are not as reliant on lithium and cobalt in the future, but such developments are unpredictable. Regardless of the changes in specifics, the fundamental issues related to the public perception of mining, the need for far more mining than ever before, and the need for immediate action to address the looming deficit, will all remain.

Public perception of mining

The poor public perception of mining and the poor public perception of the absolutely inevitable need for more mining to reach net zero by 2050 are two fundamental issues that must be addressed in order to improve societal acceptance of mining. The extent of these two challenges was highlighted when the secretary general of the United Nations, António Guterres, on opening the UN Climate Change Conference in Glasgow (COP26) in November 2021 stated, "It's time to say 'enough.' Enough of brutalizing biodiversity. Enough of killing ourselves with carbon. Enough of treating nature like a toilet. *Enough of* burning and drilling and *mining* our way deeper. We are digging our own graves" (emphasis mine).

We cannot escape the fact that there have been bad actors in the past, and even some in the present, who disgrace mining. As a specific example for one province of Canada, the British Columbia Mining Law Reform of Canada has compiled a list of the top 12 worst polluting mines in British Columbia (Berchtold, 2021). As an exemplar of an abandoned mine in northwest British Columbia, "Tulsequah Chief mine operated from 1951–1957, a relatively short time compared to the over 60 years it has been polluting the Tulsequah River. The mine leaks untreated acid mine drainage at an estimated rate of 1 million L/day that is elevated in cadmium, copper, lead, and zinc … ." (Berchtold, 2021). Similar stories are found everywhere in the world, particularly in those countries with weaker regulatory regimes and/or from legacy mine sites that were operated before the advent of environmental regulations in the 1970s.

More recently, Rio Tinto's destruction in May 2020 of two 46,000-year-old Juukan Gorge Aboriginal rock shelters in the Pilbara region of Western Australia for an iron ore mine made the news for all the wrong reasons and further tainted mining as a societally positive activity. Rio Tinto had been granted state government approval in 2013 under a legal framework to extend their operations (Wahlquist, 2020), but the public perception is that this lamentable destruction was the fault of a global mining company, not of a state government.

There is also a perception that exploration geophysics is not associated with advanced high technology but with "old" tech using 19th century physics. While it is true that most geophysical methods — including gravity, magnetics, seismics, and electromagnetism — were well defined by the mid-1800s, with James Clerk Maxwell's *A Treatise on Electricity and Magnetism* laying the foundation for the last of these, modern exploration geophysicists call upon broad skills that are arguably as difficult to master as those associated with any other science.

These two together, the poor public perception of mining and the perception that geophysics is "low tech," have the consequences that there are far too few young people opting to take training in earth sciences in general and exploration geophysics in particular. This problem is discussed further later in this paper.

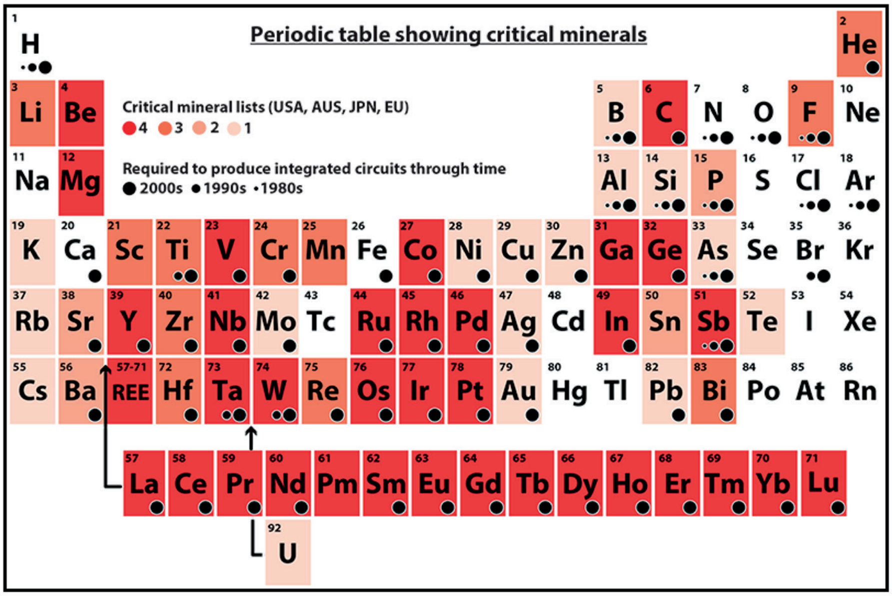

Figure 2. A periodic table of elements annotated to highlight the critical mineral lists of the United States, Australia, Japan, and the European Union. Red-shaded elements are those designated as critical minerals because of specific national concerns, global supply risk, and potential supply restriction vulnerabilities. (The lightest shading indicates that an element occurs on only one of these four countries' lists; progressively darker shading indicates occurrence on more than one list.) The dots and their size indicate elements important for integrated circuits. From Emsbo et al. (2021).

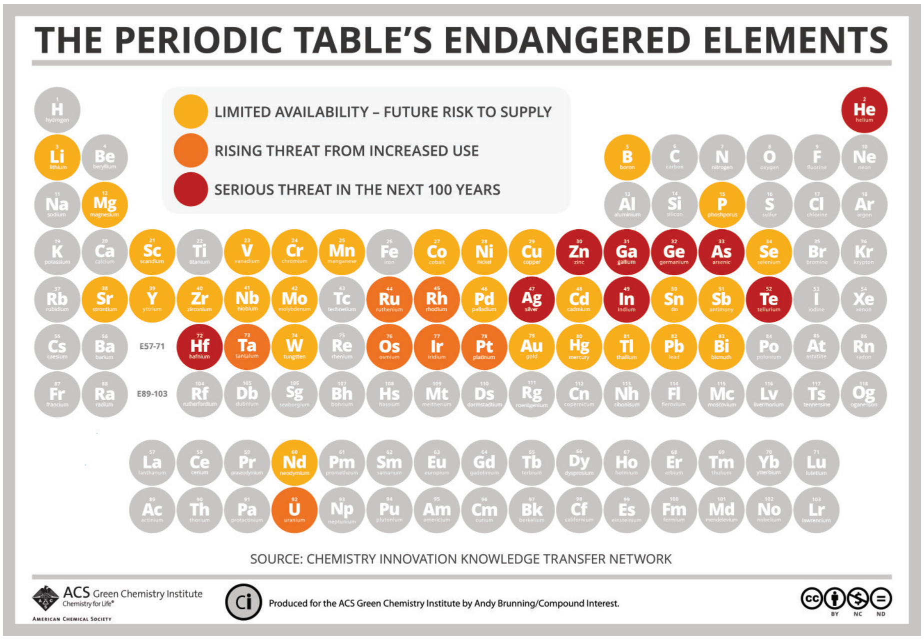

Figure 3. Endangered and critical elements. From American Chemical Society (n.d.).

Critical minerals — What are they?

Each country defines its own set of critical minerals based on economic, societal, political, and national security priorities, and the sets have varied over time. Country lists and variations with time are given in Sykes et al. (2016), Hayes and McCullough (2018), and most recently and comprehensively in McNulty and Jowitt (2021).

A comparison of the critical minerals lists of the United States, Australia, Japan, and the European Union is shown as a periodic table in Figure 2, taken from Emsbo et al. (2021). (This list was made prior to the 2022 U.S. update [USGS, 2022a].) Note that, of those four, only Japan includes copper as a critical mineral. The IEA's "Final list of critical minerals for 2022," which follows the U.S. Geological Survey's list, does not include copper (IEA, 2023). Canada has its own set of 31 defined critical minerals (Wilkinson and Champagne, 2022), and copper is included in those 31. I highlight copper as I focus on it later in this article.

Minerals and metals in renewables

Modern renewable energy and transportation technologies are extremely mineral intensive, and this has been known for two decades. One conclusion made at the United Nations 2002 World Summit on Sustainable Development was that "Mining, minerals and metals are important to the economic and social development of many countries. Minerals are essential for modern living."

We need metals and minerals for every renewable energy option available to us:

- Solar photovoltaic panels require aluminum, titanium, zinc, and magnesium for the frame; cadmium, tellurium, molybdenum, beryllium, germanium, gallium, indium, silver, and silicon for the panels; boron, phosphorus, and silicon for semiconductors; lithium, nickel, magnesium, cobalt, carbon, and vanadium for storage; and copper for transmission.
- Geothermal energy uses nickel, chromium, molybdenum, and titanium, and accounts for 80% of nickel demand and 40% of titanium demand of all low-carbon power sources (IEA, 2021).
- Wind turbines require aluminum, zinc, molybdenum, copper, iron + carbon (steel), and REEs, particularly neodymium.
- Electrical vehicles and lithium-ion (Li-ion) batteries for storage require huge amounts of copper, cobalt, nickel, lithium, REEs, aluminum, and graphite (more crucial than the metals).

For many metals and minerals, we have known global abundances. The issue is finding them in the right place for logistical efficiency reasons and also being able to extract them given environmental, societal, and governmental challenges. Jowitt et al. (2020) discuss these latter challenges and give examples of instances in which those challenges have precluded mining.

We know in principle where we should look at the regional scale, adopting the "mineral system" approach of McCuaig and Hronsky (2014) and the "mineral targeting" approach of Begg et al. (2010), as emplacement of mineralized deposits is a function of tectonic setting. Locally, fluid pathways from the deep crust to the surface can be mapped using geophysical techniques, such as magnetotellurics (MT). The most known MT image is the "Fingers of God" leading from a deep crustal conductivity anomaly vertically up to Olympic Dam and neighboring mineralized zones (Heinson et al., 2018). Major iron oxide-copper-gold deposits appear to lie on the edges of cratons (Hoggard et al., 2020), which defines an exploration strategy as expounded by the mineral system and mineral targeting approaches: first map regionally, then focus in on local areas of interesting response.

Supply risk

Many of the metals that we need for technological growth have a supply risk associated with them, either presently or looking forward. This supply risk is associated with either known deposits being exhausted or predominant reliance on one source of supply, or both. Underappreciated is the fact that production of many energy transition minerals today is more geographically concentrated than that of oil or natural gas (IEA, 2022).

One extreme example is niobium, which is sourced from the mineral columbium. Alloys containing niobium are used in jet engines and rockets, beams and girders for buildings, oil and gas pipelines, and oil rigs. Niobium is used in superconducting magnets for particle accelerators, magnetic resonance imaging scanners, and nuclear magnetic resonance equipment. Niobium oxide compounds are added to glass to increase the refractive index, which

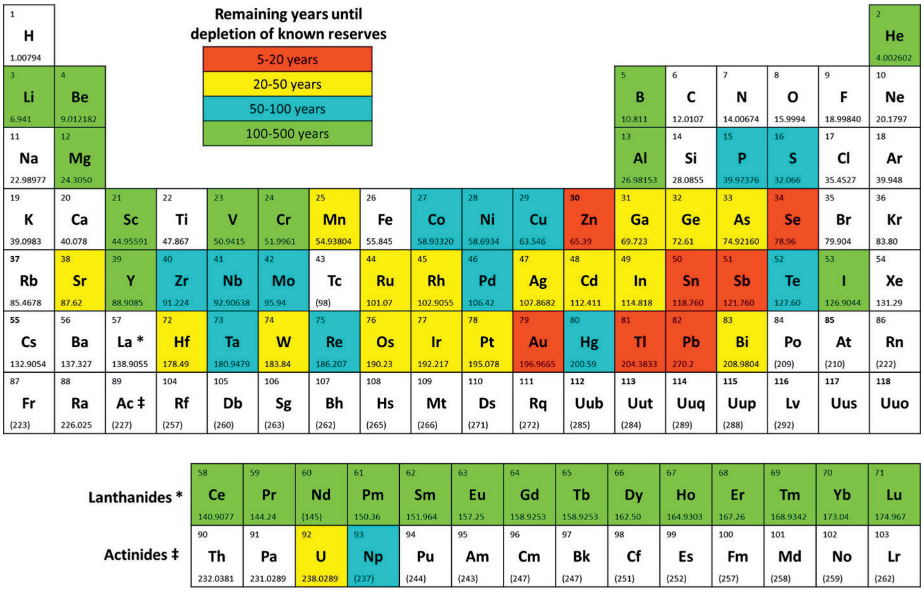

Figure 4. Remaining years until depletion of known reserves. From Supanchaiyamat and Hunt (2019).

allows corrective glasses to be made with thinner lenses. Currently, 90% of the world's production of niobium is sourced from one country, Brazil (66 Kt), with Canada producing the next highest amount (less than 10%, 7.4 Kt). The rest of the world produces 1.4 Kt. Should Brazil throttle niobium supply to the world for whatever reason, the world will struggle to ramp up production elsewhere quickly to meet the shortfall.

Some 87% of the world's magnesium is currently produced in China, although China has only 20% of the world's known reserves. Again, should supply be throttled, we will struggle to find alternate sources rapidly for automobiles, laptop computers, and mobile phones.

Production of the 17 REEs is concentrated in China at more than 80%, which is down from 95% at its peak in 2011. Throttled supply of REEs would seriously disrupt wind turbine construction, which requires neodymium. Estimates from Lee et al. (2020) are that we will need to produce 10 to 30 times the current world production of 7 Kt of neodymium by 2050 to meet the 2° warming scenario (2DS) goal for onshore wind, and 10 to possibly 50 times for offshore wind.

Emsbo et al. (2021) give a visual graphic (their Figure 2) showing concentrations by country of global critical mineral production. The asymmetry in their world map is particularly concerning.

The American Chemical Society published a list of 44 endangered and critical elements (Figure 3) that "will face supply limitations in the coming years. These critical elements include REEs, precious metals, and even some that are essential to life, like phosphorus" (American Chemical Society, n.d.).

Perhaps even more worrying is the work of Supanchaiyamat and Hunt (2019) who put a time frame on the endangered elements, and conclude that known reserves of zinc, lead, gold, tin, and antimony, all defined as critical minerals, will be depleted within less than 20 years. This analysis though may be misleading, as the authors use only reserve data (without giving reference to the source of the reserve estimates), which gives a short-term view of actual availability (Jowitt et al., 2020; Jowitt and McNulty, 2021).

Conflict minerals — The need for supply chain diligence

Some of the critical minerals sourced in the Democratic Republic of the Congo (DRC) are defined as "conflict minerals," as mining activities directly fund conflicts in that region. The so-called "3TG" minerals mined in eastern DRC that fund the conflicts are:

- columbite-tantalite (or coltan), in which tantalum occurs; tantalum is in every cell phone on the planet in tantalum capacitors;
- cassiterite, in which tin, used for tin cans and solder, is found; and
- wolframite, a source of tungsten, used in metalworking tools, drill bits, milling, and in small amounts in electronic devices, including the vibration mechanism of cell phones.

In particular, tantalum is a major concern. In 2003–2006, Australia was the world's leading supplier of tantalum, but since 2013 tantalum predominantly (more than two-thirds) comes from the African Great Lakes region. Tantalum is recycled at very low rates, which means that about two-thirds of the approximately 1.5 billion new cell phones manufactured each year (Table 7 in Belkhir and Elmeligi, 2018) have tantalum sourced from a conflict region. (Note that 85%–95% of greenhouse gas emissions due to smartphone usage come from mining, shipping ore, processing ore, and manufacture, not from actual usage [Belkhir and Elmeligi, 2018].)

To address this issue of conflict minerals, the U.S. Securities and Exchange Commission was responsible for implementing section 1502 of the Dodd-Frank Wall Street Reform and Consumer Protection Act (2010), which was related to the use of minerals determined to be financing conflict in the DRC or an adjoining country. Supply chain diligence is not assured, however, and the source of many conflict minerals is disguised. In 2019, the U.S. Government Accountability Office analysis of a sample of 2018 company filings estimated that only 56% of the companies were able to determine the country of origin of their conflict minerals (Shedd, 2022, p. 80.2), meaning 44% were unable to do so. Since 1 January 2021, the European Union requires supply chain diligence of tantalum to remove tantalum's financing of conflicts.

Let's have "ethical minerals," just like ethical diamonds and ethical foods

Some companies have signed on to the Responsible Minerals Initiative (RMI), the European Partnership for Responsible Minerals, and the Public-Private Alliance for Responsible Minerals

Trade. The RMI currently has standing cooperation agreements or cross-recognition agreements with multiple industry initiatives, including:

- Responsible Cobalt Initiative
- International Tin Association
- International Copper Association
- Responsible Mica Initiative
- Responsible Jewellery Council
- London Bullion Market Association

As an exemplar, Seagate, a leader in storage devices, has a "responsible sourcing of minerals" policy that establishes the company's commitment to ethical sourcing practices. Seagate employs a team of senior-level professional staff to provide continual supply chain diligence and oversight, ensuring that they uphold their commitment to maintain a responsible supply chain. Seagate reports its sourcing as part of its filing to the U.S. Securities and Exchange Commission. As sensitivity to the interwoven complexities of supply chain economics becomes more visibly mainstream among industry leaders — and the public — we may see a broader adoption of such self-reporting behaviors.

In a broader context, we need to be concerned not only about conflict minerals but accessing all of the at least 30 energy transition minerals and metals (ETMs). A recent study by Owen et al. (2022) of 5097 ETM projects, georeferenced against various indicators, showed that more than half of the ETM resource base "is located on or near the lands of Indigenous and peasant peoples, two groups whose rights to consultation and free prior informed consent are embedded in United Nations declarations."

Transitioning to renewables must not come at the cost of environmental degradation or human rights abuses.

Copper — The impending supply deficit

Although few people and few countries think of copper as a critical mineral, it is essential for absolutely everything to do with the move to a renewable energy and transportation future. And the need for copper is increasing exponentially.

One goal in the IEA's Net Zero 2050 road map is to reduce the number of cars that use internal combustion engines (ICEs) to zero and ramp up the number of electric vehicles (EVs). The road map calls for 60% of global car sales to be EVs by 2030, which is in only 7 years' time, and no new ICE sales by 2035, 12 years' time. A number of major automobile manufacturers have stated that they will adhere to COP26 and not build any ICEs after 2035 (including Ford, Mercedes-Benz, Volvo, Jaguar Land Rover, and General Motors; however, Volkswagen, Toyota, Renault-Nissan, and Hyundai-Kia have refused to sign up). Is this feasible from a copper perspective alone, never mind the other metals required?

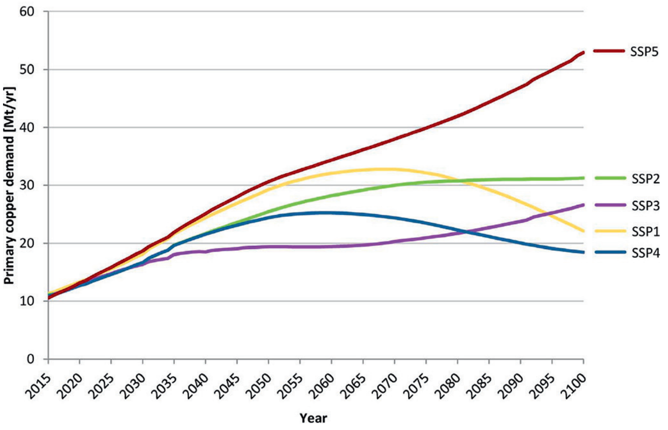

Figure 5. Annual copper demand by SSP narrative assuming a recycling rate of 90%. From Schipper et al. (2018).

According to the Copper Development Association, a typical ICE needs 9–20 kg of copper, a typical hybrid EV needs 60 kg, and a battery EV (BEV) needs 83 kg , and the same ×20 multiplier for trucks and buses. (These numbers may reduce when/if moving to 48v electrical systems and to innovating wiring design.) Other estimates exist, but what they all have in common is the far greater need for copper in EVs, by a factor of approximately 5–10. There are currently some 1.4 billion vehicles on the roads globally — 1 billion cars and 400 million trucks and buses. Approximately 100 million new vehicles are built every year. Indeed, car production alone was almost 100 million in 2018 and 2019. If all of those 100 million new vehicles are to be BEVs, then we need roughly 15 Mt of copper to make them. The current copper recycling rate is 55%, meaning we need some 7 Mt of new copper every year for BEVs.

We can add to that number the increased needs of copper for wind and solar. Estimates are that solar will increase from currently 0.6 to 2 Mt of copper by 2050, offshore wind from 0.06 to 0.4 Mt, and onshore wind from 0.45 to 0.86 Mt. Taken all together, and assuming a 55% recycling rate, we need an additional 1 Mt of copper every year for these purposes.

On top of these are the increasing copper needs for grid infrastructure, charging points for EVs, and more. Globally, there is approximately 150 Mt of copper in the installed base of overhead lines, underground cables, and transformers, with a typical lifetime of 40–60 years. More than 20 Mt of installed copper needs to be replaced by 2030, and a similar amount by 2040. Growth of 75% in grid infrastructure is estimated for the IEA's SDS scenario (IEA, 2022). Grid infrastructure adds another 2 Mt of new copper required.

Thus, by 2035 we need to be extracting and producing at least 10 Mt of new copper.

Current world production of copper is approximately 21 Mt/annum. So this has to increase to at least 30 Mt/annum by 2035, with some estimates as high as 50 Mt/annum (Bonakdarpour and Bailey, 2022). Personal use of copper is expected to double between now and 2050 (Bonakdarpour and Bailey, 2022), which is consistent with increasing copper demand since the 1950s. Mined copper production increased 6.5 fold between 1956 and 2018, with a per capita increase of approximately 2.5 times (Jowitt, 2022). *Over the next 20–25 years, the world is going to need to mine more copper than has been mined in all of human history.*

Copper demand under the various SSP narratives has been calculated by Schipper et al. (2018), and the projection for our best-case narrative, SSP1, is that we will need to be mining an astonishing 100 Mt/annum by 2100. Assuming a (highly unlikely)

90% recycling rate, this can be reduced to a peak of 35 Mt/annum (Figure 5). However, one must remember that the more copper there is in circulation, the more there is to recycle, but the copper has to come into circulation in the first place in order for it to be recycled!

The problems are that[5]:

1) More than 200 major copper mines currently in operation will reach the end of their productive life before 2035 (Mills, 2020).
2) Current copper production of 20 Mt/annum is projected to fall to 12 Mt/annum by 2035 (Mills, 2020).
3) Copper grades in the world's two largest mines, namely the copper porphyries of Chile, Escondida, and Collahuasi, which together generate some 25% of global production, have been steadily decreasing from 1.41% in 2000 to 0.65% in 2016 (Jamasmie, 2018). The copper production at both mines has remained relatively constant, but twice as much rock must be extracted and processed now compared to 2000. This tonnes-grade curve decrease is true of other metals and minerals also.
4) Copper deposits are far smaller and far deeper than have been found in the past, and the discovery rate is severely decreasing. The number of significant discoveries peaked at 184 in 2010, and we are now at less than half that rate (Schodde, 2020). We have not found a new supergiant deposit in more than 25 years (Emsbo et al., 2021).
5) Unit cost per discovery has increased significantly from on average $65 million from 1970 to 2005 to more than $200 million today (Schodde, 2020). The amount of drilling required rose from 237,000 m in 2005 to 680,000 m in 2017. (Schodde, 2019).
6) Looking 8 years forward in 2008 there were 60 projects planned that would bring 4.8 Mt/annum of new copper. However, as of 2020, there are only 36 projects to 2027 that will bring only 1.74 Mt/annum of new copper into production (Kettle, 2021).
7) It takes far longer to bring a prospective deposit to a producing mine now than it did some 70 years ago. In the 1950s, 50% of prospective discoveries became mines within 15 years. Each decade since then, the rate of discovery-to-mine has decreased. It is now at 9% for 2000–2016.
8) There is significant concentration of global production of copper in four countries, namely Chile (27% of global production at 5.6 Mt in 2021), Peru (2.2 Mt), DRC (1.8 Mt), and China (1.8 Mt) (USGS, 2022b). This poses a potential supply risk, as discussed earlier.
9) Prolonged industrial action can severely throttle copper production over relatively short time scales, but they can have knock-on effects that persist for longer time scales due to ramping-up requirements and investment anxiety. Peru is the second largest copper producer, and, currently, 30% of its production is imperiled due to violent protests (Attwood, 2023). This comes at a time when global stockpiles of wiring metal are at historically low levels. In addition, societal unrest jeopardizes investment in new mines. In the example of Peru, the industrial action jeopardizes the rollout of $53.7 billion in possible investments.
10) As a recent and pertinent example of political and legislative barriers to addressing supply gaps of energy transition metals, First Quantum Minerals was forced to halt operations at its Cobre Panamá open-pit copper mine in early January after failing to agree to tax levels and royalties under a new contract. Talks are progressing and will undoubtedly be successful, but production is halted in the meantime.

Lithium supply deficit

A supply deficit is also projected for many other metals and minerals essential for achieving net zero, particularly for lithium and cobalt required for Li-ion batteries for EVs and energy storage (Figures 11.8 and 11.6, respectively, in Giurco et al., 2019). The possible shift from Li-ion to lithium-sulfur batteries will result in even greater demand for lithium.

Electrochemical energy conversion (EEC) storage systems are required for wind power generation to solve the baseline power problem. An estimate from the Energy Futures Lab, Imperial College London is that for the United Kingdom alone "Over 140 GW of grid-connected batteries will be needed in Britain, a more than 100-fold increase on the volume in use today, to help even out supply and demand and ensure security of supply in a system dominated by intermittent renewables."

Lee et al. (2020) present World Bank estimates that 12 times as much lithium will need to be produced for Li-ion batteries to meet the maximum 2DS goal by 2050. As well, we will need to produce 12 times as much aluminum, cobalt, iron, lead, manganese, and nickel. If we only produce double what we are producing today, then we will hit the 4°C warming scenario.

A recent analysis of demand by Benchmark Mineral Intelligence (BMI) estimates at least 384 new mines for graphite, lithium, nickel, and cobalt will be required to meet EV demand by 2035 (Benchmark, 2022). Even if battery materials can be recycled in large enough quantities, BMI estimates that nevertheless about 336 new mines would be needed.

The price for Li-ion cells has plummeted more than 97% over the last 30 years, from $7500/kWh in 1991 to $198/kWh in 2018 (both in 2018 US$) (Ziegler and Trancik, 2021) to a minimum of $141/kWh in 2021 then a slight rise to $151/kWh in 2022 (the latter two in 2022 US$; BloombergNEF, 2022). Predictions are that the cost of Li-ion cells will drop further to below $100/kWh by 2026, especially with greater adoption of lithium iron phosphate (LFP) lower-cost cathode chemistry cells, and further reduction of cobalt in nickel-based cathodes. LFP cells were, on average, 20% cheaper than conventional lithium nickel manganese cobalt oxide cells in 2022 (BloombergNEF, 2022). However, these cost reductions are unsustainable, and indeed are likely to be reversed, without increased supply of the metals and minerals needed, which will throttle EV acceptance and EV replacement/EV battery replacement in the longer term.

Lithium comes today primarily from three countries, 46.3% from Australia (40 Kt production in 2020), 23.9% from Chile

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[5] Note: Some of these estimates are contested by Mudd and Jowitt (2018).

(20.6 Kt), and 16.2% from China (14 Kt), with known reserves concentrated predominantly in Chile (48.5%, 9.2 MT) and Australia (24.8%, 4.7 MT) (Bhutada, 2022). This is a worrying supply risk.

Canada currently has no lithium production and a paltry 2.5% of known world reserves of lithium, but this is an expression of how little of Canada's geology has been mapped given the similar tectonic histories of Canada and Australia. Production is expected in 2023 from a lithium mine at La Corne, Quebec, but the mine has had a problematic history of serious and damaging spills and has filed for creditor protection twice in the last decade — despite a \$110 million investment from the provincial government (McKenna, 2022). Other potential lithium mines from the same operator, Sayona, are being resisted by First Nation's peoples because of their proximity to fresh water essential to the Anishinabeg. This one example of the problems present in opening a mine exemplifies the broad range of difficulties faced when trying to bring a deposit to production.

IDTechEx projects that 12 Mt of Li-ion batteries will be recycled by 2042 and that recycling will become a \$50 billion industry (Holland, 2021). A Li-ion battery is typically 7% by weight in lithium, so the recycled amount of lithium would be approximately 900 Kt. This is significant, as current world production of lithium is 100 Kt for 2021, and projected production in 2030 is only 1.1 Mt, whereas projected desired production is approximately 2.6 Mt by 2030 under the IEA's SDS (IEA, 2022). Production of 1.1 Mt does meet IEA's STEPS, but such a scenario would not assure net zero by 2050.

Cobalt is another essential metal for Li-ion batteries, by approximately 55% of the total battery weight. Currently, more than 70% of the world's production of cobalt of 140 Kt comes from the DRC, and this has tripled since 2008. Not only is this a dangerous dependency, but while cobalt is not defined as a conflict mineral per se, cobalt mining is associated with child labor, crime, corruption, poverty, and hazardous artisanal mining. To address these issues, the Fair Cobalt Alliance was created in August 2020 to "assist in the building of a DRC cobalt mining sector that is known to be a responsible partner in providing the minerals needed for a new green economy."

Other battery chemistries are being explored as alternatives to Li-ion and lithium-sulfur, such as nickel-hydrogen, sodium-ion, magnesium-ion, zinc-ion, aluminium-ion, and metal-sulphur. There are pros and cons for each of these (Vendigital, 2022). In most cases, they are lower in energy density than Li-ion and thus are impractical for EVs, but they offer potential solutions for EEC storage.

Shipping — The ignored cost

One cost often ignored when considering the global emissions of greenhouse gases is that of shipping. Estimates are that maritime shipping generated 1 billion tons of greenhouse gases (CO_2-equivalent) per year in 2007–2012 (Schim van der Loeff et al., 2018; Trimmer and Godar, 2019). This is some 3% of global greenhouse gas emissions. Shipping is also responsible for 15% of nitrogen oxides emissions and 5%–8% of anthropogenic sulphur oxides emissions.

Of the UN's Harmonized Commodities, commodity HS26, which is ores, slag, and ash, represents that largest commodity to be shipped, by far, and the longest distances to be shipped, again by far (Trimmer and Godar, 2019), and produces more than 56% of total shipping emissions (Schim van der Loeff et al., 2018). It is estimated that the main components for construction of a Li-ion battery, namely lithium, cobalt, and nickel, travel some 50,000 miles, with raw ore shipped from Chile, DRC, Madagascar, Australia, Russia, etc. to China for processing, then to Japan for cathode production, and finally to the United States for cell production.

We can reduce this cycle by sourcing "locally," which means more exploration, particularly deeper exploration, in most cases. Local mining of course would require local smelting in order to significantly reduce shipping cost.

Metals companionality

Perhaps unappreciated by most members of the public, and indeed likely underappreciated by most geophysicists, is "metals companionality." Many metals essential for the energy transition are produced as by-products of mining for something else. The periodic table in Figure 6 (from Nassar et al., 2015) shows in red all those elements that we obtain through mining for other metals and minerals. Many of them are on the critical minerals lists of many countries.

For example, when mining for zinc, we obtain indium, germanium, and cadmium as by-products, all essential for touch screens, LEDs, fiber-optic cables, semiconductors, cadmium telluride solar panels, etc. Mining for these by-products themselves would be prohibitively costly. As shown in Figure 5,

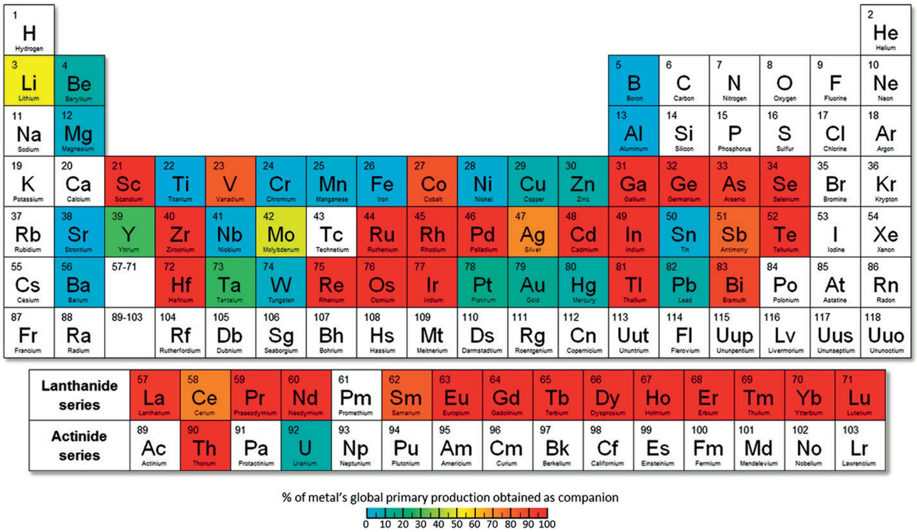

Figure 6. Periodic table showing metals companionality by color coding. From Nassar et al. (2015).

known deposits of zinc may be exhausted within 20 years, thus depriving us of indium, germanium, and cadmium in the future unless we find and exploit new zinc deposits quickly.

Nassar et al. (2015) also present an informative "wheel of metal companionality" (their Figure 2) that links the metals. In their figure, the principal host metals form the inner circle, and companion elements appear in the outer circles at distances from the inner-circle host metals proportional to the percentage of their primary production (from 100% to 0%).

Training of skilled talent — A bleak picture for the 2030s and 2040s

Earth science generally and exploration geophysics in particular are not attracting students to enter appropriate courses at universities, resulting in reduced enrollments since the mid 2010s (Boone et al., 2021; Nature Reviews Earth & Environment, 2021; Cohen, 2022). For Australia there has been a 38% drop in undergraduate enrollments in the geosciences (from 3485 in 2013 to 2158 in 2017), for the United Kingdom a 24% drop (from 6105 in 2016 to 4645 in 2019), for the United States a 29% drop (from 31,819 in 2016 to 22,741 in 2020), and for Canada an approximate 37% drop (from approximately 5200 in 2015 to approximately 3300 in 2021) (Boone et al., 2021; Cohen, 2022).

The decline in the United Kingdom has been attributed to a parallel reduction in geology course offerings in primary and secondary schools (Boatright et al., 2019), whereas in the United States it is attributed to the 2019–2021 "shrinkage in employment prospects" in the U.S. petroleum, mining, and geologic engineering industries (Boone et al., 2021). For the United States alone, the American Geosciences Institute estimates that there will be a talent deficit of 130,000 geoscientists by 2029 (Gonzales and Keane, 2020).

The secondary effect is that we are not training sufficient numbers of people in broad exploration geophysics subdisciplines to become university professors for training future generations. For example, the teaching of potential field theory and application, if done at all, is no longer done by those with deep knowledge and experience in potential fields. The same with electromagnetic theory: there are very few electromagnetics-focused professors at Western universities compared to a generation ago.

There has been a measurable shift in higher education toward adoption of incentive-based "responsibility center management" strategies for resource management, and not without controversy (e.g., Hearn et al., 2006). The consequences of the reduced enrollments and the business model of universities is that earth science departments are having to cope with significant staff reductions, either actively (as with closing down Macquarie's Earth Science Department) or passively through not replacing those who leave. Even in the event that an exploration geophysicist retires and the position can be retained by the earth science department, the replacement is often not in mineral exploration geophysics. Of course, we need people in broad earth science topics, such as climate change, at our universities, but we also need those knowledgeable in exploration geophysics.

Added to this is that universities operate as isolated fiefdoms unto themselves, with little regard for coordinated national needs. Each country should have a broad review of earth science teaching, particularly exploration geophysics teaching, across its nation, and rationalize it into focused centers appropriately located in a geographic/geologic sense.

Of the 10,338 paid Society of Exploration Geophysicists members (as of 30 September 2022) who reported their age (85% of total paid membership), 44% are over age 55 and only 23% are under age 35 (SEG, 2022). We are an aging profession. We do not need a lot of exploration geophysicists to futureproof our needs, not like engineering, law, or medicine, but we need enough to be trained. We simply are not going to have enough young, trained exploration geophysicists in the 2030s and 2040s to reach net zero by 2050. We also have a serious issue regarding diversity in the geosciences generally that needs to be addressed if we are to retain talent (Marin-Spiotta et al., 2023).

The challenge to attracting students is to present the earth sciences generally, and exploration geophysics in particular, as extremely interesting, curiosity driven, and intellectually challenging using advanced mathematical, numerical, and computational methods to contribute positively to societal needs now and in the future. The challenge at universities is to train and educate geophysicists broadly, so they have mobile, adaptable, transferable skills. And the challenge to industry is to partner with universities to build joint programs where students will see positive, modern potential careers in the energy transition space.

Conclusions

The importance of understanding and addressing climate change cannot be overstated. If we do not act with alacrity, the fate of humanity will be in peril — not within the lifetimes of half of SEG members, but certainly within the lifetimes of those under 35.

The overarching issues holding back exploration geophysics are (1) the poor social acceptance of mining, (2) a lack of appreciation for the need for mining to ensure we are able to combat a globally warming planet, and (3) the decreasing enrollment numbers into the earth sciences at universities. These issues require broad, swift action. The issues are diverse and complex, but we have a societal imperative and responsibility to address them. TLE

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Data and materials availability

All information presented herein is in the public domain.

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