Critical Materials For Energy Transition

June - 2021

Sustainability Report

The Al-Attiyah Foundation

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INTRODUCTION

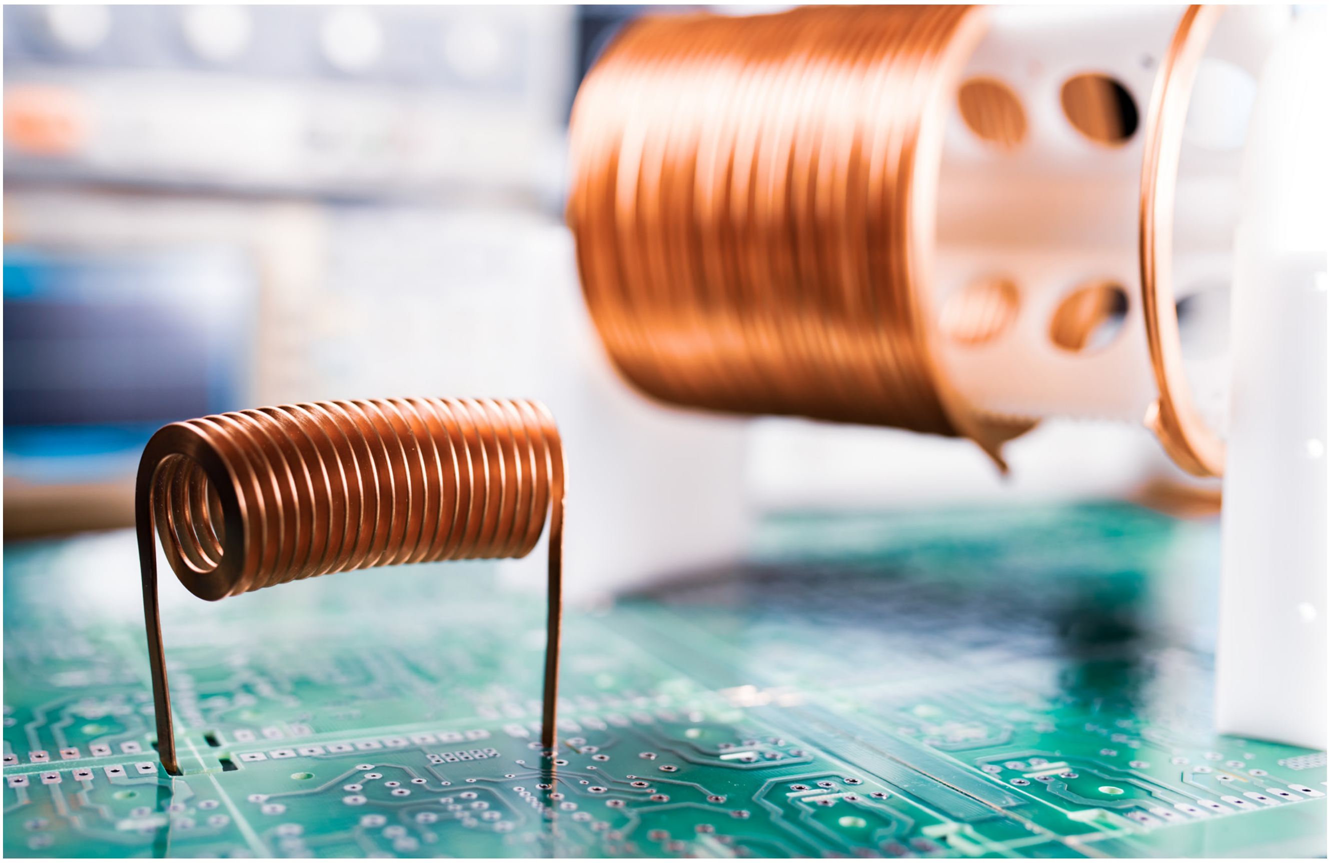
CRITICAL MATERIALS FOR ENERGY TRANSITION

The emerging new global energy system requires new materials that were not traditionally in high demand. Their currently known reserves are often small, technically difficult to obtain, or concentrated in politically challenging countries. Governments and companies are paying growing attention to ensuring that the clean energy transition can access sufficient quantities of such materials at reasonable prices.

What are the key materials for energy transition? What critical components are required for solar, wind, battery and other new energy systems? How will supply and demand of each evolve, and where are they located? What can be done to substitute, recycle or reduce the use of each? What are the geopolitical implications associated with the availability of such materials?

Sustainability Report

This research paper is part of a 12-month series published by The Al-Attiyah Foundation every year. Each in-depth research paper focuses on a prevalent sustainable development topic that is of interest to The Foundation's members and partners. The 12 technical papers are distributed to members, partners, and universities, as well as made available online to all Foundation members.

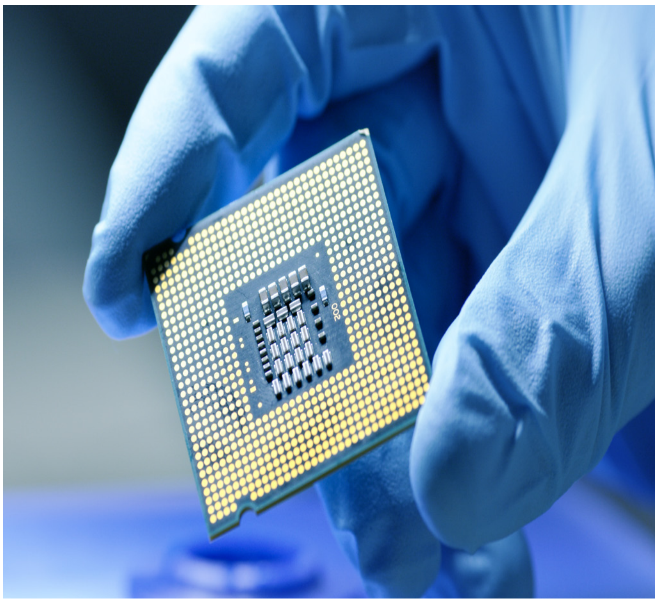


EXECUTIVE SUMMARY

- Critical minerals have become increasingly important as new energy systems require new minerals that were not in high demand previously.
- The main drivers of increased demand are electric vehicles, battery storage and electricity networks. Solar and wind power mineral requirements are important but secondary.
- Traditional materials that will see strongly increased demand include copper, silver and graphite.
- 'Emerging' materials that were not in strong demand previously include lithium, cobalt, nickel and rare earth elements (REEs).
- These minerals are often found with high reserves, production and processing capacity, in geopolitically or environmentally challenging areas.
- China is particularly dominant in many of these minerals, and to a lesser extent Russia and the US.
- Supplies can be threatened by producers' market power, underinvestment, geopolitical competition, and unexpected extraneous events due to lack of many options to diversify supply.
- Price rises, volatility and unexpected shortfalls or interruptions in key mineral supply have the potential to slow cost declines for new energy and so hamper the transition to low-carbon energy.
- Technological improvements can help increased mined output, including unconventional sources. More importantly for sustainability, new approaches can boost material efficiency use, recycling and the availability of alternatives.
- International cooperation between governments is required to improve mineral social and environmental sustainability, facilitate trade and ensure security of supply.
- The geopolitics of critical minerals have some similarities to that of oil and gas, but can be different in some ways – policymakers have to be careful not to fall into old paradigms.
- Cartels, embargoes and mineral-rich rentier states are much less likely to occur or to be successful with minerals than historically with petroleum.

WHAT ARE THE CRITICAL MINERALS AND WHAT ARE THEY USED FOR?

The classification of essential energy materials by uses and in different jurisdictions, is shown in Table 1. There is a considerable degree of overlap, although some minerals are included which may be critical for non-energy applications rather than energy, and some minerals are not included because, although critical, they are readily available. For example, aluminium on the IEA and Japanese lists, and silicon on the EU, US, Japanese and Canadian lists. There are some surprising exclusions, such as copper and silver that are not on the EU or US lists, despite their importance in electric wiring and motors. Overall, 14 materials or groups of materials appear on the critical lists of all five entities: cobalt, gallium, germanium, graphite, indium, lithium, magnesium, niobium, platinum-group, rare earth elements (REEs), tantalum, titanium, tungsten and vanadium. India's Critical Minerals Strategy[i] identified 49 materials of which 12 were considered of particular importance and at risk: beryllium, chromium, germanium, graphite, light and heavy REEs, limestone, niobium, rhenium, silicon, strontium, tantalum and zirconium. From a supply perspective, Russia has a much shorter list of 'strategic deposits', which covers diamonds, high-purity quartz, the yttrium group of REEs, nickel, cobalt, tantalum, niobium, beryllium, lithium and the platinum group, and especially large copper or gold deposits[ii].



Most extra growth in essential mineral demand will come from electric vehicles, battery storage and electricity networks. Grids will be greatly expanded to meet the electrification of the global economy, as transport, heating and many industrial processes are converted to run on electricity. Solar photovoltaic (PV) and wind have a lesser but significant role in mineral demand. In the International Energy Agency's Sustainable Development Scenario (SDS), the use of lithium would rise 42 times by 2040, graphite 25 times, cobalt 21 times, nickel 19 times and rare earths 7 times.

It should be noted that, over time, some minerals may leave the critical list while others are added to it. On the other hand, a few critical minerals are experiencing declines in demand. This particularly applies to some of the less important REEs, europium, terbium and yttrium, because of their declining use for fluorescent lighting.

WHAT ARE THE CRITICAL MINERALS AND WHAT ARE THEY USED FOR?

TABLE 1 ESSENTIAL ENERGY MATERIALS[iii]

<table>
<tr><th rowspan="2">Mineral / material</th><th colspan="5">Critical List</th><th rowspan="2">Main energy uses</th></tr>
<tr><th>EU</th><th>IEA</th><th>US</th><th>Japan</th><th>Canada</th></tr>
<tr><td>Aluminium / bauxite</td><td>✓</td><td></td><td>✓</td><td></td><td>✓</td><td>Solar and wind turbine structures, electricity transmission lines</td></tr>
<tr><td>Antimony</td><td>✓</td><td></td><td>✓</td><td>✓</td><td>✓</td><td>Battery storage for renewable energy, glass production</td></tr>
<tr><td>Arsenic</td><td></td><td>✓</td><td>✓</td><td></td><td></td><td>Lead storage batteries</td></tr>
<tr><td>Barite</td><td>✓</td><td></td><td>✓</td><td></td><td></td><td>Petroleum and geothermal well drilling fluids</td></tr>
<tr><td>Beryllium</td><td>✓</td><td></td><td>✓</td><td></td><td></td><td>Heat-transfer medium in nuclear reactors</td></tr>
<tr><td>Bismuth</td><td>✓</td><td></td><td>✓</td><td></td><td>✓</td><td>Additives for lead-free pipe fittings; fuel elements for nuclear energy generation</td></tr>
<tr><td>Borate / boron</td><td>✓</td><td>✓</td><td></td><td></td><td></td><td>Solar thermal heating applications, insulation, safety and control of pressurized water reactors in nuclear plants, battery applications</td></tr>
<tr><td>Caesium</td><td></td><td></td><td>✓</td><td></td><td>✓</td><td>Photoelectric cells and energy conversion devices</td></tr>
<tr><td>Chromium</td><td></td><td></td><td>✓</td><td>✓</td><td>✓</td><td>Nuclear reactor alloys</td></tr>
<tr><td>Cobalt</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>Batteries, permanent magnets for wind power and bioessential for renewable biogas technology</td></tr>
<tr><td>Coking coal</td><td>✓</td><td></td><td></td><td>✓</td><td></td><td>Steel production</td></tr>
<tr><td>Copper</td><td></td><td>✓</td><td></td><td>✓</td><td>✓</td><td>Electric wiring, motors</td></tr>
<tr><td>Fluorspar</td><td>✓</td><td></td><td>✓</td><td>✓</td><td>✓</td><td>Aluminium and uranium processing, steelmaking</td></tr>
<tr><td>Gallium</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>Integrated circuits (in high-tech equipment), light emitting diodes (LEDs), CIGS solar cells</td></tr>
<tr><td>Germanium</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>Solar cells, other solar energy applications</td></tr>
<tr><td>Gold</td><td></td><td></td><td></td><td>✓</td><td></td><td>Glassmaking, gold bonding wires within semiconductor packages</td></tr>
<tr><td>Graphite</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>Battery applications, steelmaking, refractory applications, foundry operations, brake linings</td></tr>
<tr><td>Hafnium</td><td>✓</td><td>✓</td><td>✓</td><td></td><td></td><td>Control rods in nuclear reactors and nuclear submarines</td></tr>
<tr><td>Helium</td><td></td><td></td><td>✓</td><td></td><td>✓</td><td>Nuclear fusion</td></tr>
<tr><td>Indium</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>Electrical conduction, mercury substitute in batteries, nuclear reactor control rods, liquid crystal displays (LCDs), energy-efficient street lighting, CIGS solar photovoltaics</td></tr>
<tr><td>Iridium</td><td></td><td>✓</td><td></td><td></td><td></td><td>High-temperature corrosion-resistant material, spark plugs</td></tr>
<tr><td>Lead</td><td></td><td>✓</td><td></td><td>✓</td><td></td><td>Lead-acid batteries</td></tr>
<tr><td>Lithium</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>Li-ion batteries (EVs, renewable back-up)</td></tr>
<tr><td>Magnesium</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>Agriculture, chemicals, construction, and industrial applications</td></tr>
<tr><td>Manganese</td><td></td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>Cobalt substitute in batteries</td></tr>
<tr><td>Molybdenum</td><td></td><td>✓</td><td></td><td>✓</td><td>✓</td><td>Catalyst for hydrogen production, energy storage and conversion, alloying agent in cast iron, steel and superalloys</td></tr>
<tr><td>Nickel</td><td></td><td>✓</td><td></td><td>✓</td><td>✓</td><td>Nuclear reactor alloys, NiMH batteries, electrolysers</td></tr>
<tr><td>Niobium</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>Battery energy density, steel and super alloys</td></tr>
<tr><td>Palladium</td><td rowspan="2">✓</td><td></td><td rowspan="2">✓</td><td>✓</td><td rowspan="2">✓</td><td>Fuel cells, electrolysers, catalytic converters</td></tr>
<tr><td>Platinum[1]</td><td>✓</td><td>✓</td><td>Fuel cells, electrolysers, catalytic converters</td></tr>
<tr><td>Phosphate</td><td>✓</td><td></td><td></td><td></td><td></td><td>Fertiliser, feedstock for chemical processing</td></tr>
<tr><td>Phosphorus</td><td>✓</td><td></td><td></td><td></td><td></td><td>Manufacturing wooden and paper safety matches, pesticides, fertilisers</td></tr>
<tr><td>Potash</td><td></td><td></td><td>✓</td><td></td><td>✓</td><td>Fertiliser, feedstock for chemical processing, glass manufacturing</td></tr>
<tr><td>Rare earths (light)[2]</td><td>✓</td><td>✓</td><td rowspan="2">✓</td><td>✓</td><td rowspan="2">✓</td><td>Permanent magnets (EVs, wind turbines)</td></tr>
<tr><td>Rare earths (heavy)[3]</td><td>✓</td><td>✓</td><td>✓</td><td>Permanent magnets (EVs, wind turbines)</td></tr>
</table>

[1] The US and Canada lists refer to 'platinum group metals', which covers platinum, palladium, iridium, osmium, rhodium and ruthenium, the first two being by far the most important in applications.

[2] Cerium, lanthanum, praseodymium, neodymium and samarium; also sometimes includes scandium which has similar properties but is not strictly speaking a REE, and is separately on the EU, US and Canadian lists.

[3] Yttrium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium, basically equivalent to the "yttrium group" in Russian classification.

TABLE 1 ESSENTIAL ENERGY MATERIALS[iii]

Rubber (natural)	✓					Vehicle tyres
Rubidium			✓			Photocells manufacturing, propellant in ion engines on spacecraft
Scandium	✓		✓		✓	Ceramics, electronics, lasers, radioactive isotopes, lighting, lightweight aluminium alloy, solid oxide fuel cells
Selenium		✓				CIGS solar cells efficiency
Silicon		✓				Solar cells, electronics
Silver		✓		✓		Solar cells, renewable energy storage
Strontium	✓		✓	✓		Additive in drilling fluids for oil and gas wells
Tantalum	✓	✓	✓	✓	✓	Capacitors for electronic devices
Tellurium		✓	✓		✓	CdTe solar cells
Tin		✓	✓	✓	✓	Circuit boards
Titanium	✓	✓	✓	✓	✓	Aerospace applications
Tungsten	✓	✓	✓	✓	✓	Catalyst for energy converting reactions in solar cells, wear-resistant materials used in construction and metal making
Uranium			✓		✓	Nuclear fuel
Vanadium	✓	✓	✓	✓	✓	Steelmaking, aerospace applications
Zinc		✓			✓	Wind turbine blade coating, batteries
Zirconium		✓	✓	✓		Electrolysers, nuclear reactor alloys, furnace linings

WHERE ARE THESE MATERIALS OBTAINED?

Unlike oil and gas, critical minerals are widely dispersed and few if any countries have large reserves of all (Table 2). China, Russia, the US, Australia, Brazil and Canada are importantly represented across reserves of numerous critical minerals. But some particularly key ones are dominated by geographically smaller countries, for instance Chile and Peru for copper, Chile for lithium, Morocco for phosphates, and South Africa for the platinum group. Production does not simply follow reserves, for instance China tends to produce more of some of the minerals, than many countries with proven larger reserves. Australia is not a leading miner of tantalum despite dominating the reserves total. This can be because of environmental or other barriers to mine development, or because a particular country's resources are of low quality.

The dominance of China is particularly striking when looking at the number of minerals for which it is the world's largest miner, far ahead of any other country (Table 3). Also, because of its high demand, China is a large importer of many of these materials despite its domestic production. Given its particular strategic importance in copper, Chile might be ranked quite highly even though it leads only in one mineral.

Many of these minerals have not historically been economically important, or are by-products of mining other minerals. Therefore, exploration for them has been limited and data may be unreliable, and may not properly distinguish technically and economically recoverable resources from mere occurrences. With additional exploration, price rises and technological improvements, many additional sources for these resources are likely to become viable.

Substantial mining of some materials, such as tin in Brazil and Myanmar and cobalt in the Democratic Republic of Congo (DRC), is carried out by artisanal and small-scale miners (ASM) who do not report reserves or production figures. About 30% of REE mining in China may be illegal and unreported to avoid imposition of government quotas.

WHERE ARE THESE MATERIALS OBTAINED?

TABLE 2 LEADING GLOBAL RESERVES HOLDERS AND PRODUCERS[iv]

Material	Top 3 reserves holders			Top 3 producers		
Antimony	China 32%	Russia 23%	Bolivia 21%	China 74%	Tajikistan 8%	Russia 4%
Barite	Kazakhstan 27%	China 11%	Turkey 11%	China 32%	India 12%	Morocco 10%
Aluminium	-	-	-	China 52%	Russia 7%	Canada 5%
Beryllium	US 60%			US 72%	China 22%	
Bismuth	China 65%	Vietnam 14%	Mexico 3%	China 80%		
Borates	Turkey 87%	US 4%	Russia 4%	Turkey 43%	US 25%	
Coal	US 23.3%	Russia 13.9%	China 13.2%	China 47.6%	Indonesia 9%	US 8.5%
Cobalt	DRC[4] 53.3%	Australia 17.8%	Cuba 7.4%	DRC 64%	Russia 5%	Australia 4.2%
Coking coal	-	-	-	China 55%	Australia 16%	
Copper	Chile 22.3%	Peru 10.8%	Australia 10.11%	Chile 28.4%	Peru 12%	China 8.2%
Fluorspar	Mexico	China	South Africa	China 65%	Mexico 15%	
Gallium	-	-	-	China 81%		
Germanium	-	-	-	China 80%	Russia 5%	US & Japan, 2% each
Hafnium	-	-	-	France 49%	US 44%	China, Russia and Ukraine
Indium	China 69%	Peru 3%	US 1.3%	China 48%	South Korea 21%	EU 9%
Lithium	Chile 43.8%	Australia 22.4%	Argentina 9%	Australia 52%	Chile 28.4%	China 12.5%
Magnesium	-	-	-	China 89%	US 4%	
Molybdenum	China 46 %	Peru 15.5%	US 15%	China 44.2%	Chile 19%	US 14.8%
Natural gas	Russia 19.1%	Iran 16.1%	US 14%	US 23.1%	Russia 17%	Iran 6.1%
Natural graphite	China 23.1%	Brazil 22.8%	Brazil 7.9%	China 60.2%	Mozambique 13.2%	Brazil 8.3%
Natural rubber	-	-	-	Thailand 37%	Indonesia 25%	
Nickel	Indonesia 22.3%	Australia 21.3%	Brazil 17%	Indonesia 32.7%	Philippines 12.4%	Russia 10.7%
Niobium	~Brazil 94.1%			Brazil 91.6%	Canada 7%	
Oil	Venezuela 17.5%	Saudi Arabia 17.2%	Canada 9.8%	US 17.9%	Saudi Arabia 12.4%	Russia 12.1%
Platinum group	South Africa 91.3%	Russia 5.7%	Zimbabwe 1.7%	Russia 43.2%	South Africa 35.5%	Canada 8.8%
Phosphate & phosphorus	Morocco 70.4%	China 4.5%	Egypt 3.9%	China 41.8%	Morocco 15.6%	US 10.26%
REE	China 35%	Brazil 18%	Russia 17%	China 63%	USA 12%	Australia 8%
Scandium						
Silicon	-	-	-	China 68%	Russia 7.3%	Norway 4.5%
Silver	Peru 18.2%	Australia 17.6%	Poland 14%	Mexico 22.3%	Peru 14.6%	China 13.0%
Strontium	-	-	-	Spain 40.9%	China 22.7%	Mexico 18.2%
Tantalum	Australia 70.7%	Brazil 28.6%		DRC 31.4%	Brazil 23.2%	Rwanda 18.2%
Tellurium	China 21.3%	US 11.29%	Canada 2.5%	China 60.9%	Japan 12.6%	Russia 9.1%
Tin	China 25.6%	Indonesia 18.6%	Australia 10%	China 28.5%	Indonesia 26.18%	Myanmar 14.18%
Titanium	Australia 28.3%	China 26.1%	South Africa 7.1%	China 42.5%	Japan 24.5%	Russia 22%
Tungsten	China 58%	Canada 9%	Vietnam 3%	China 82%	Russia 4%	Vietnam 4%
Uranium	Australia 28%	Kazakhstan 15%	Canada 9%	Kazakhstan 41.7%	Canada 12.7%	Australia 12.1%
Vanadium	China 48%	Russia 25%	South Africa 18%	China 39%	South Africa 32%	Russia 25%

[4] Democratic Republic of Congo

As Figure 1 shows, for most minerals, reserves and production roughly correlate. However, for some, like magnesium, caesium, rubidium, thallium, the available reserves are far in excess of any likely use. Yet some others, such as gallium, tungsten, copper and chromium, have quite short reserves lives at current mining rates (19-35 years), indicating new resources have to be explored and appraised in the near future.

For many of these minerals, processing is as important or more important to the cost and complexity of the supply chain, than mining. This particularly applies to the rare earths, which are chemically complicated to separate and often contaminated with radioactive elements, and to the enrichment of uranium to levels useful for nuclear fuel. China is by far the leading country, in the processing of essential minerals, with rates at: 35% of nickel, 50-70% of lithium and cobalt, and almost 90% for REEs[vi]. Notwithstanding, its high production and/or processing rates,

TABLE 3 RELATIVE RANKING OF MAIN MINING COUNTRIES

Country	Number of critical minerals of which it is producer #...		
	1	2	3
China	21	2	3
USA	3	4	4
DRC	2	0	0
Russia	1	6	7
Indonesia	1	3	0
Chile	1	2	0
Brazil	1	1	1
Canada	0	2	2
Australia	0	1	2
Other	6	14	9

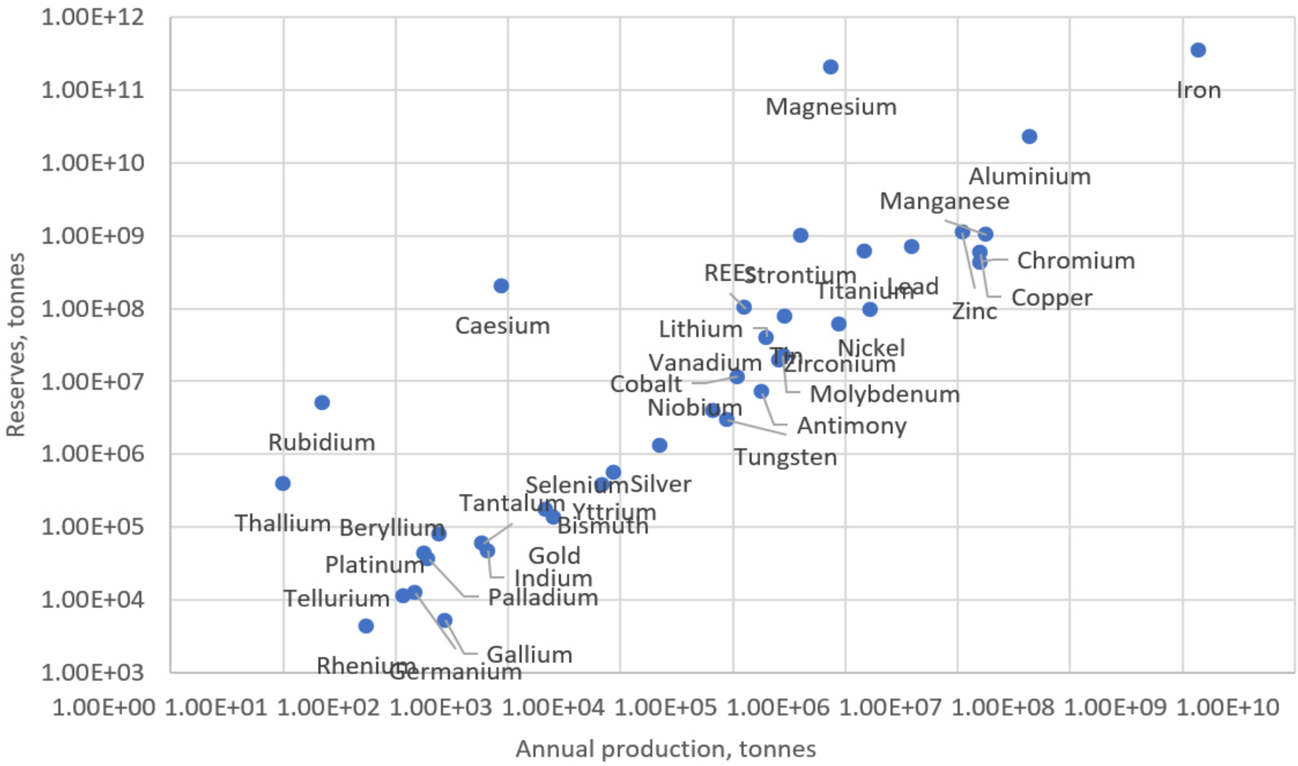
WHERE ARE THESE MATERIALS OBTAINED?

China is also the world's leading importer of copper, iron ore, chromium, manganese, cobalt, tantalum, niobium, platinum-group metals and lithium[vii].

During 2010-20, prices for the most critical materials showed no consistent upward or downward trend (Figure 2). But prices have accelerated for various minerals during 2021 because of demand recovery from the Covid-19 pandemic, and massive economic stimulus plans in the US, Europe and China. This has led to predictions of a new commodity 'super-cycle' similar to that in the early 2000s, and driven by economic expansion along with heavy investment in new energy technologies and infrastructure. In May 2021, copper prices reached a record of $10,417 per tonne, beating $10,160 per tonne from February 2011[viii].

In comparison, the current global revenues from coal mining are about ten times those from mining 'energy transition' minerals. However, it is projected that by 2040, revenues from the production of transition minerals will overtake coal. The largest such minerals by revenues will be, in declining order, copper, nickel, lithium, graphite and cobalt.

FIGURE 1 RESERVES AND PRODUCTION OF SELECTED MINERALS[v]



WHAT ARE THE MAIN CHALLENGES AND THREATS TO CRITICAL MINERALS?

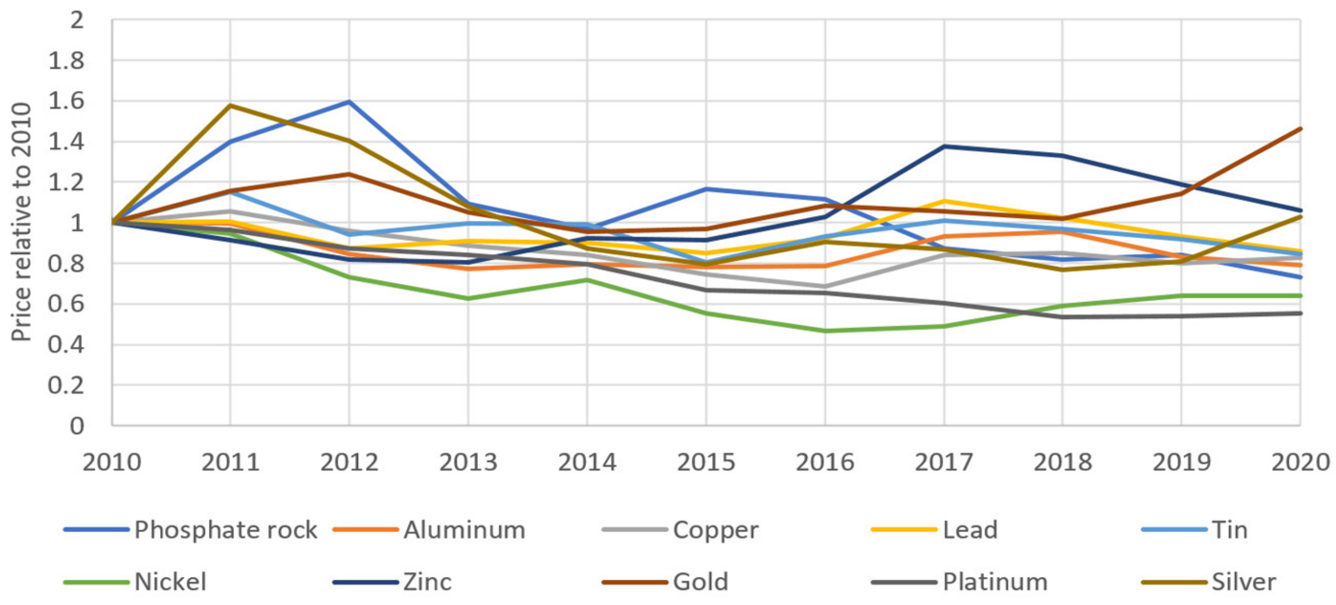
The challenges to critical minerals vary between the different materials, but can be broadly classified into four groups:

- Security, social and environmental issues
- Market power by concentration of reserves, production and processing
- Barriers to investment
- Geopolitical and geoeconomic competition and disputes.

Mining often causes environmental damage. New mines face growing opposition, particularly but not solely in developed countries. This is likely to be a challenge for attempts to increase domestic self-sufficiency in Europe and North America. For instance:

- Codelco of Chile, the world's largest copper producer, has said 40% of its output could be threatened by a new bill banning mining operations near glaciers[ix].
- The Pebble Mine in Alaska, which holds gold, silver, copper, palladium, molybdenum and rhenium, has been delayed for more than a decade over concerns on the effect on fishing and tourism[x].
- The Twin Metals copper-nickel-cobalt-platinum group mine in Minnesota, faces a possible Congressional ban on mining due to concerns about the effect of acid contamination on the Boundary Waters[xi].
- BHP has spent $2 billion and 26 years on the Resolution copper mine in Arizona, which would be one of the world's largest underground mines, but has been held up by environmental concerns and Native American sacred sites[xii].
- The Woodsmith polyhalite and potash mine in North Yorkshire, UK, also faced about a decade of delay in development, due to complex environmental protections for the national park[xiii].
- Norilsk is one of the world's largest miners of nickel, copper, cobalt, platinum and palladium, but the city in Siberia is one of the world's most polluted due to the associated smelting activities, with high levels of sulphur dioxide and heavy metals. In May 2020, a diesel storage tank owned by a Norilsk Nickel subsidiary collapsed because of melting permafrost, causing severe damage to rivers.

FIGURE 2 PRICE DEVELOPMENT OF SELECTED CRITICAL MINERALS SINCE 2010



The greenhouse gas (GHG) emissions of mining and smelting are substantial, particularly for iron, aluminium and copper which rely on large quantities of coal, iron and/or gas. Remote mines often operate on diesel generators for power and have large amounts of heavy diesel-fuelled equipment such as trucks. However, mines are beginning to install renewable energy or look into carbon sequestration options to lower their GHG footprint.

Energy use in metal extraction varies widely (Figure 3). Ores with low metal concentrations have high energy requirements, notably platinum-group metals, gold, zirconium, silver and tin. REEs, particularly have high energy consumption, because of the complexity of separating the different elements. Mining and processing of low grade copper is also quite energy-intensive, given the large volumes involved. The pattern in water intensity is quite similar, which can be problematic in water-stressed mining areas such as Chile, the south-western US, north-west Africa and Australia.

FIGURE 3 ENERGY USE IN METAL EXTRACTION[xiv]

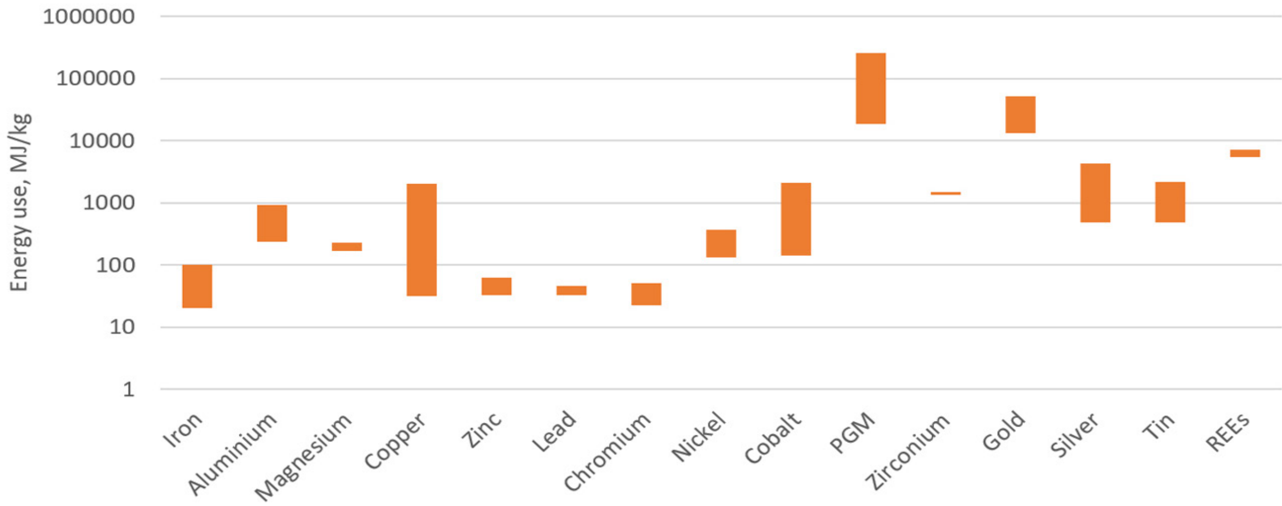
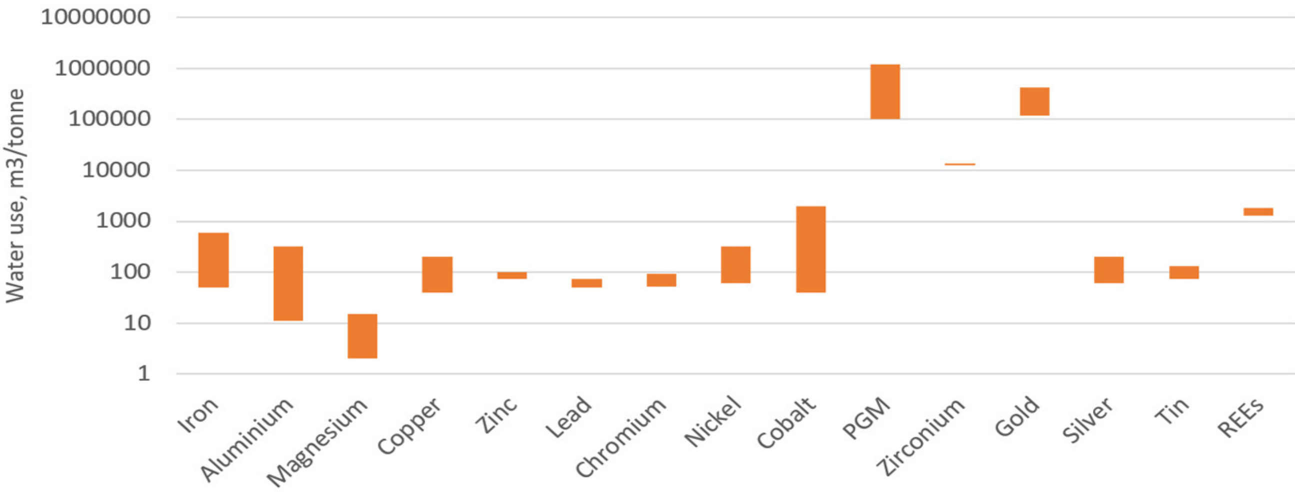


FIGURE 4 WATER USE IN METAL EXTRACTION[xv]



Mines also have social impacts, that could be both positive and negative. ASM play an important role for some minerals, such as tin, and their Often disputes between local communities and central governments, result in disruption of mining operations. In Indonesia for example, disputes with the government, have often disrupted supplies of tin. Strikes and labour disputes are common in the mining industry, for instance in Marikana, South Africa, where 34 strikers at a platinum mine were shot dead by police in 2012. Mines and mineral export routes, like oil-fields, can be threatened by criminals, hostile non-state groups, factions in civil wars, revolutionary regimes and other security dangers. The 'Three TG' conflict minerals – tantalum, tin, tungsten and gold – have been blamed for fuelling conflict in the DRC.

Market power could be used in different ways: to raise prices by controlling supply; to punish political opponents or deter or threaten military rivals by restricting their access to key materials; or to favour domestic manufacturers and the development of key technological or military capabilities by preventing their competitors from accessing raw materials.

WHAT ARE THE MAIN CHALLENGES AND THREATS TO CRITICAL MINERALS?

Past attempts at metals cartels have not succeeded, and have certainly not had anywhere close to the same influence that OPEC has had on the oil market. For instance, the Intergovernmental Council of Copper Exporting Countries (CIPEC), founded in 1967, attempted to restrain supply and so increase prices in 1974-76, but were frustrated by insufficient compliance and competition from outside the group[xvi]. Indonesia, Thailand and Malaysia in 2004 formed the International Rubber Consortium, aiming to stabilise (and probably increase) the price of natural rubber, but studies suggest its efforts have been counterproductive[xvii].

However, such attempts could recur and might be more successful if organised by a superpower such as China. For instance, since October 2020, China has been coordinating the efforts of its manganese processing companies, leading to price increases[xviii]. China has also invested extensively in mines internationally, such as lithium in Australia, rare earths in the US and cobalt in the DRC, although these holdings do not necessarily have any strategic or monopolistic intent.

Investment barriers could include nationalisation of resources, tax increases, unfavourable investment conditions, and supply-chain constraints.

As prices for critical metals increase, governments seek to raise additional revenues, worsening the economics or deterring investment. Chile, the world's largest copper producer, is considering raising royalty rates on copper to bring in funds for social programmes, threatening 1 million tonnes per year of future output, according to Goldman Sachs, and Peru, the second largest producer, is also proposing higher taxes on the metal. In May 2021, the DRC reinstated an export ban

on copper and cobalt concentrates, to encourage domestic smelting. However, processing in the DRC is limited by power shortages[xix].

Even with strong future demand, metals prices remain volatile and prone to cycles of over- and under-supply. Major mining corporations are still under shareholder pressure to restrict investment and return dividends. Smaller firms can easily be bankrupted by a fall in price or problems in developing a large, remote project, as happened to Nemaska Lithium in May 2020, which spent more than CA$400 million on a lithium project in Quebec but ran out of money to fund infrastructure.

Supply-chain constraints relate to the speed with which new major mines can be explored, permitted and developed. For instance, Bernstein calculates 10.4-14.6 Mt per year of new copper mining is required to meet demand from electric vehicles and other emerging uses, which could require $100 billion of investment. That equates to 12 new mines over the decade, each the size of Escondida or Collahuasi (the world's two largest copper mines). However, there have been few recent major copper discoveries, other than Cascabel in Ecuador and Quellaveco in Peru. The Kakula project in DRC is a rare large new mine which may produce about 530 000 tonnes of copper annually[xx], but needs a waiver from the country's export ban. Only four EPCM (engineering, procurement, construction and management) companies worldwide (Wood, SNC, Bechtel and Fluor), would be able to build such projects, and they have limited capacity and are likely to be working on projects for other metals as well. This constraint is in addition to the delays related to technical, environmental and government regulatory requirements, that are usually common with such large projects.

Geopolitical and geoeconomic barriers include the threats that countries could cut off supplies of critical minerals to hostile countries in the case of trade disputes or conflict, or reduce exports in order to support domestic industries or forestall competition from international rivals. Conversely, major monopolistic buyers of minerals could cut purchases from a certain country to put political pressure on it. As with oil, sanctions regimes may target minerals.

WHAT METHODS AND POLICIES CAN BE USED TO SAFEGUARD SUPPLIES?

Policies so far have revolved around three main areas:

- Reduction of amounts of new critical materials required by efficiency, improved technology, substitution and recycling
- Increased supply and strategic stocks, domestically and internationally
- International cooperation to strengthen supply chain robustness.

Higher prices and shortages, as well as deliberate policies by governments and companies, will decrease the amount of primary minerals required. Recycling of REEs was less than 1% in 2011[xxi] and 15% in 2014. However, recycling of gold was 95% and aluminium 75% in 2014[xxii]. Recycling can be challenging because devices are not designed for it and metals are mixed in components, making them metallurgically hard to separate, particularly given the wide variations in types of waste. There is currently no technology to recover gallium, germanium and tantalum. More innovative recycling and recovery techniques, better product design, and incentives or standards, would help increase recycling rates[xxiii]. This applies especially to batteries, cars and electronic devices.

Higher prices and threatened shortages have encouraged attempts to reduce and substitute rare material use. For instance, cerium, a common REE, can be used instead of rarer neodymium and dysprosium in magnets[xxiv]. Copper-indium-gallium-selenide (CIGS) and cadmium telluride (CdTe) can be replaced by common silicon solar cells. Already, cobalt has gradually been replaced by higher levels of nickel in lithium-ion batteries. New battery designs, such as lithium-iron-phosphate, lithium-air and lithium-aluminium, could replace cobalt and nickel[xxv], while lithium could be substituted with aluminium, sodium or zinc, or vanadium redox-flow batteries.

On the side of increased supply, higher prices and heightened investor interest will of course increase mining (and recycling) to a degree. This can include life extensions and expansions at existing mines, new exploration, and the exploitation of lower-grade or more challenging resources.

For instance, major new lithium mines were commissioned in Mexico, Nevada (US), Western Australia, Quebec (Canada), Mali and Zimbabwe[xxvi]. Pilot plants are being tested to extract lithium from the Salton Sea brines in California in combination with geothermal energy. Thermal waters in Germany's Rhine Valley contain potentially exploitable quantities of lithium (and also caesium and rubidium)[xxvii], as do oil-field brines produced in western Canada and in the Permian Basin of West Texas[xxviii].

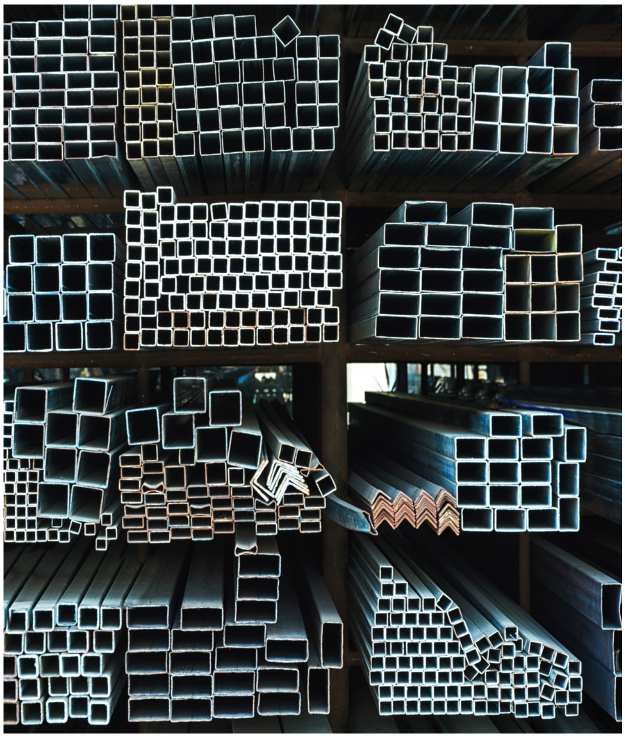
REEs are mostly extracted from monazite, xenotime, fluorcarbonates and loparite minerals, but research is underway to extend this to a wider range of minerals[xxix].

Sea-floor metals are of increasing interest, with three main groups[xxx]:

- Polymetallic nodules, scattered over large areas of the abyssal plain, containing nickel, cobalt, copper and manganese;
- Crusts, containing mostly cobalt and manganese with vanadium, molybdenum, tellurium and platinum;
- Massive sulphides, usually associated with high-temperature hydrothermal vents, containing copper, lead, zinc, gold and silver.

A sea-mount crust near the Canary Islands has been demonstrated to have tellurium in concentrations 50,000 times higher than on land, as well as REEs[xxxi]. A Japanese expedition has suggested that submarine mining would be feasible. However, the geology is not yet well-understood, and some settings are less promising for metals that may have been leached away over time. Perhaps more critically, the deep-sea environment is little-known and very sensitive. Disturbance of sediment can choke organisms.

Many rarer metals are not or rarely mined and smelted on their own but are by-products of other ores, notably tellurium and selenium (from copper and zinc), platinum and palladium (nickel), rhodium (partly dependent on nickel and platinum), gold (partly dependent on silver, copper and platinum), indium (copper-zinc), gallium (bauxite/aluminium), cobalt (copper, nickel and platinum), silver (partly dependent on copper and lead) and rhenium (molybdenum)[xxxii].



Recovery of these by-products could be significantly increased by greater awareness from miners of the primary metals, and better processing techniques[xxxiii].

Some governments are investing directly and providing incentives such as tax breaks and easing permitting or environmental regulations, and construction of supporting infrastructure in remote mining regions. For example, Russia is seeking to invest $1.5 billion in rare earth minerals to become the leading supplier after China by 2030[xxxiv].

In contrast, recent reports suggest that the Biden Administration in the US will have a strategy of boosting international cooperation, relying on ‘friendly’ countries such as Australia, Brazil and Canada for critical materials, rather than encouraging domestic mining, because of environmentalist opposition. Programmes such as the Energy Resource Governance Initiative aim to work with allies to produce cobalt, lithium and other EV metals.

WHAT METHODS AND POLICIES CAN BE USED TO SAFEGUARD SUPPLIES?

The US, is however, introducing incentives for domestic materials processing and manufacturing. For instance, the Pentagon is funding construction of Lynas's heavy rare earth separation facility in Texas. The US government has since April been the biggest shareholder in TechMet, a mining investor with projects in tungsten in Rwanda, nickel in Brazil and battery recycling in Canada. The country is funding research into cobalt in Canada, rare earths in Malawi, and extracting REEs from coal waste in the US.

There are many international cooperation initiatives focusing on the social and environmental sustainability of minerals, such as, the Initiative for Responsible Mining Assurance[xxxvi], the Extractive Industries Transparency Initiative[xxxvii], and the Equator Principles[xxxviii]. The scope of some of the initiatives includes the role for responsible artisanal and small-scale mining, given that it employs some 100 000 people in the DRC alone[xxxix].

In comparison to oil, strategic minerals are usually easier to stockpile as they are solid (so can be stored in warehouses), usually not easily flammable or explosive, and are used in much smaller quantities. In 2020, the US Department of Defence submitted a request for $5 billion to expand its stocks of critical minerals[xl]. As with oil, companies or countries could be legally required to hold a minimum number of days of their mineral use or imports. Like-minded countries could also pool their strategic stocks, and commit not to impose trade restrictions.

WHAT ARE THE GEOPOLITICAL IMPLICATIONS?

Critical minerals are often seen as repeating many of the geopolitical vulnerabilities of oil and gas, but in fact they are quite different[xli]. Copper, iron, aluminium and other metals have already been important commodities for most of the industrial era, but with rare exceptions, they have not played an important geopolitical or geoeconomic role.

Despite their importance, the critical minerals markets are not very large.

- The global rare earth market was valued at $2.8 billion in 2018, lithium was $4.23 billion in 2019, cobalt is about $7 billion, while the combined copper, nickel, lead and zinc market (much of which is not for critical or energy-related uses) was $111.5 billion in 2020.
- In the IEA's SDS scenario, yearly revenues from the main 'transition minerals' for clean energy uses would reach about $260 billion by 2040, of which $110 billion is copper.
- By contrast, the world oil market is worth about $2.4 trillion per year at current prices, and the LNG market around $150 billion.

The direct macroeconomic impact of price spikes is therefore not very large. Apart from small or very low-income countries with large deposits, critical minerals will not create super-rich 'rentier' states or become the dominant feature of a national economy, as oil has done over the last half-century in countries such as Venezuela or the GCC.

However, critical minerals are particularly more at risk in one way: unlike oil and gas, which are mostly exported by small- and medium-sized countries of limited geopolitical power

(Russia and, from recent times, the US, being the exceptions), a whole swathe of critical minerals mining and processing is dominated by China and, to a lesser extent, the US and Russia.

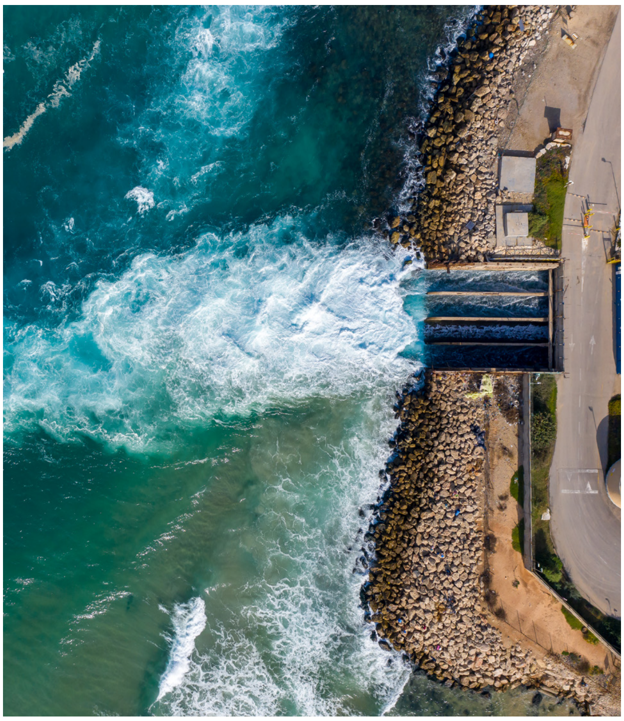
Export bans can be used as tools to support domestic users of materials, such as the Chinese battery industry, but this can only work to a limited extent before competitors develop alternative supplies or new products not reliant on the scarce material. For example, Japan was able to overcome the Chinese REE export limits imposed in 2010. However, the EU, with its green ambitions to develop its high-tech energy industries, may be concerned to be so dependent on three major competitors – China, the US and Russia – for so many vital inputs.

IMPLICATIONS FOR LEADING OIL AND GAS PRODUCERS

The IEA's 'Net Zero' report proposes a very rapid path towards reaching global net-zero carbon dioxide emissions by 2050. This demands a very rapid scale-up of the use of EVs, batteries, solar and wind power, hydrogen and other energy sources reliant on critical minerals. Although the IEA has considered such materials in its study, they still pose a significant constraint on a very rapid energy transition. Critical minerals may not be physically available, may be disrupted by the increased market or political leverage their suppliers have, or, most likely, will experience substantial price rises which would make some new energy systems less economically competitive.

This has to be taken into account when oil and gas producers assess the market for their products. There may be more market for other low-carbon solutions, such as carbon capture and storage, that are not so dependent on rare minerals. On the other hand, the ramp-up of 'green' hydrogen could be limited by material constraints on electrolysers.

Petroleum operations also yield some critical minerals, especially the potential for extraction of lithium from oil-field associated water. Oil and gas producers could investigate diversification and 'natural hedges' by investing in strategic minerals for EVs and renewables. As noted, Russia in particular, as a major oil and gas exporter, has large resources of some critical minerals, as do Canada, the US, Australia and Brazil. The Middle East has not been heavily explored for minerals, though Iran is a large miner of copper, Saudi Arabia has gold and phosphates, Oman copper, chromite, silver and gold, and Saudi Arabia and Iran have some potential for uranium. Some countries might have metal resources in their deep-sea areas. The Gulf states are heavy users of desalination of seawater to produce potable water, and there is the possibility of developing techniques to recover minerals including lithium, magnesium, molybdenum, nickel, zirconium, vanadium, gold and uranium from desalination residues[xlii]. Oil and gas producers could also invest in international projects or mineral mining and processing companies.

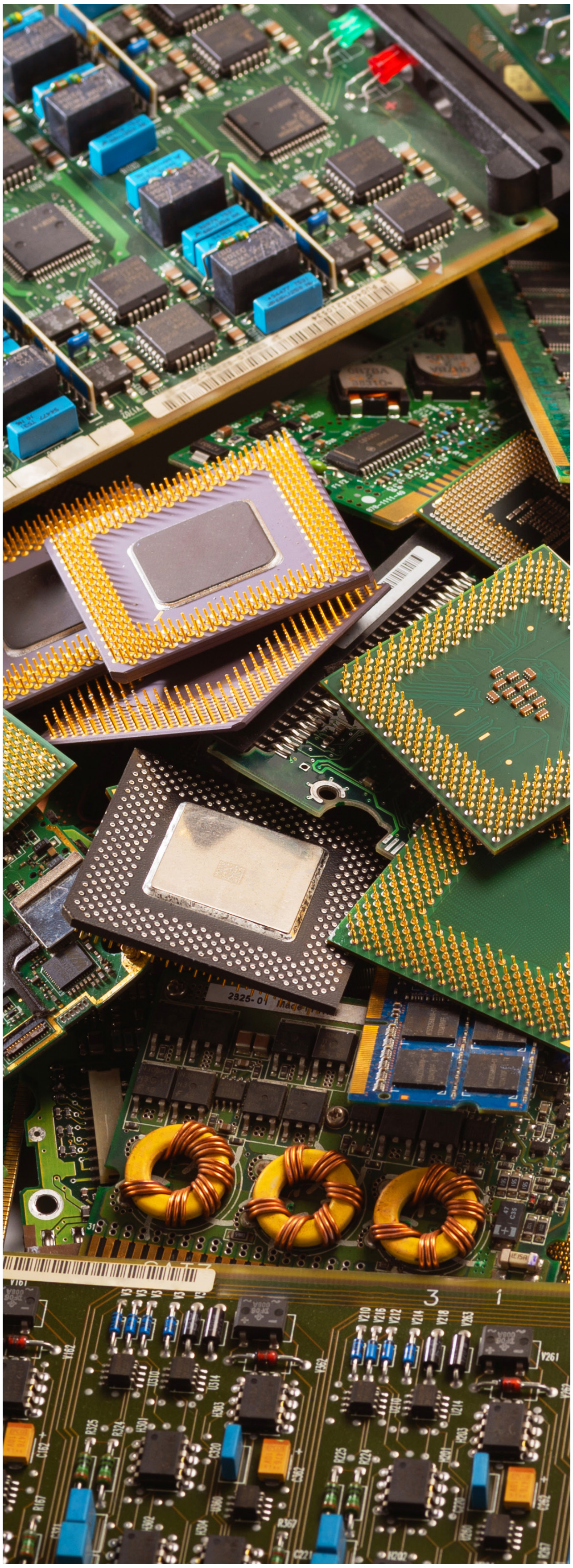


CONCLUSIONS

With the continuing forecast on transition to new energy systems, critical materials, mostly metals, have come under growing attention. Some are commonly-used today but will see growing demand, such as copper, while others have historically been unimportant but are now finding important applications. Although major consuming countries and blocs identify long and varying lists of critical materials, there is a fair degree of consensus on a much smaller group of essential ones.

There is probably excessive attention on the geopolitical risks to these materials, notably rare earths from China, and insufficient focus on the simple need for more investment, given the governmental, community-related and environmental obstacles to new and expanded mines, and shortages of industry capacity. Also, mining production tends to be over-emphasised, to the exclusion of constraints on smelting and processing, and recycling.

To ensure a secure and reasonably-priced supply of critical materials, international cooperation is preferable to attempting autarky or subsidising uneconomic output.



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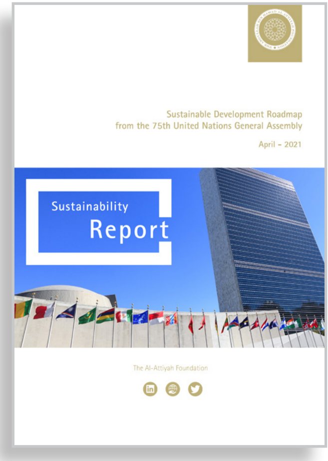

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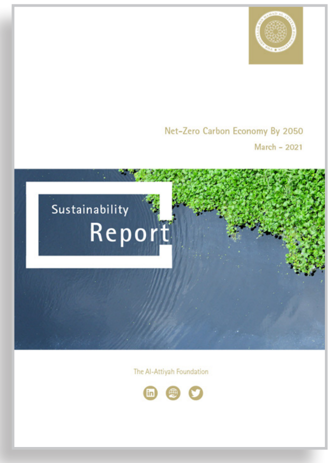

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