I·M3 Institute of Materials, Minerals & Mining

Meeting Critical Raw Materials' demand

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The global network for the materials cycle

Impediments and solutions to meeting the world's demand for Critical Raw Materials

Abbreviated title: Meeting Critical Raw Materials' demand

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Abstract

Recent flooding and extreme heatwaves around the world have heightened concerns about the need to meet Net Zero and other 'green' targets. Politicians in many countries recognise this, as well as appreciating the dominance of certain countries, China in particular, across the Critical Raw Materials (CRMs) supply chain. What few understand, however, is that we need to significantly increase the supply of CRMs if we hope to meet Net Zero and other ESG targets. While most forecasters anticipate a substantial increase in latent demand, there is one major and uncomfortable truth. Once inventories have been used, actual consumption can only rise at the rate of actual supply. If we wish to meet environmental targets and reduce supply dependence on certain countries, then we need to assist and not hinder mineral development. This means simplifying (not removing) planning, environmental, taxation and ownership criteria via better collaboration amongst all stakeholders, and better provision of finance. In the longer term, the mining industry needs to improve its image, not least because we need to attract more talented people into the industry. In short, we need to present the mining industry as part of the solution, and not part of the problem.

This paper reviews what CRMs are, the supply and demand challenges (with a focus on lithium), and what is being done, and what can be done, by the mining and end-user industries, financial markets, politicians and the citizens of the world to ensure that we have a viable planet for generations to come.

What makes some raw materials more critical than others?

Over the last few years, the availability of Critical Raw Materials (CRMs) has become one of the key considerations for both industry and politicians as the world grapples with rapidly evolving changes in demand, the desire to go 'green' and the concentration of supply at various stages of the supply chain amid the geopolitical ramifications of these three key factors. Barely a day goes by without the publication of a report or public commentary stressing the need to resolve these issues, from global organisations, governmental or ministerial groups, non-governmental organisations (NGOs), commodity and other research groups, and mining and other industrial enterprises.

Geopolitical concerns define Critical Raw Materials

Castro-Sejin et al. (2023) note that several factors determine criticality. These include geological scarcity (both globally and within national boundaries), geopolitical instability (impacting availability and consistent supply), commodity prices (which may impact demand, supply and substitution) and end-use applications (which will be impacted by demand trends, technological innovation and national industrial requirements). In general, however, and as noted by the UK's House of Commons Foreign Affairs Committee (2023), 'Critical minerals supply is not a geological challenge but a geopolitical one'. There are therefore several factors that come in to play when looking at broader geopolitical risk, and these have helped a number of countries to shape their list of CRMs, see Table 1.

The British Geological Survey (2024) provides useful analysis on the determination of criticality. The national lists, which are periodically updated, are primarily derived from national needs, less domestic capability to supply, and therefore differ for each country. Most countries have 26-36 minerals on their list, with the USA the greatest at 52, primarily because the US lists Rare Earth Elements (REEs) and Platinum Group Metals (PGMs) individually. Indeed, the USA publishes two lists; that of the Geological Survey, which looks at criticality from a domestic perspective and is retrospective, while the Department of Energy publishes a similar list (with some differences) which looks at criticality from a global perspective and looks forward to 2035. The EU has two lists, 34 commodities on its CRMs list, and 17 on a strategic raw materials list (all of which are also on the CRMs list). The UK has a list of 18 critical minerals, plus a further 8 candidate materials, all 26 of which are shown on Table 1. Australia also has two lists, covering 36 commodities, having added a list of strategic materials in December 2023 to the updated list of critical minerals (Australian Government 2023, Australian Minister for Resources and Minister for Northern Australia 2023). Canada added three additional materials to its earlier list in June 2024; high-purity iron, phosphorus and silicon metal (Canadian government 2024). South Africa's list is designed around stimulating domestic mineral exploration, hence its list contains only 14 CRMs.

Table 1 – Critical and Strategic Raw Materials' lists for different countries

MINERALS	US	EU	Japan	UK	Australia	Canada	S. Korea	India	S.Africa
	Feb-22/ Jul-23	Nov-23	Oct-19	Jun-22	Dec-23/ Feb-24	Jun-24	Feb-23	Jul-23	Apr-22
Alumina (high-purity)		✓			✓				
Aluminium	✓	✓			✓	✓	✓		
Antimony	✓	✓	✓	✓	✓	✓	✓	✓	
Arsenic	✓	✓			✓				
Barium/barite	✓	✓	✓						
Bauxite		✓							
Beryllium	✓	✓	✓	✓	✓			✓	
Bismuth	✓	✓	✓	✓	✓	✓	✓	✓	
Boron/borates		✓	✓						
Cadmium							✓	✓	
Carbon			✓						
Caesium	✓		✓			✓			
Chromium	✓		✓		✓	✓	✓		✓
Coal									✓
Cobalt	✓	✓	✓	✓	✓	✓	✓	✓	✓
Coking Coal		✓							
Copper	✓	✓			✓	✓	✓	✓	✓
Feldspar		✓							
Fluorine/fluorspar	✓	✓	✓		✓	✓			
Gallium	✓	✓	✓	✓	✓	✓	✓	✓	
Germanium	✓	✓	✓	✓	✓	✓		✓	
Graphite	✓	✓		✓	✓	✓	✓	✓	
Gypsum									
Hafnium	✓	✓	✓		✓			✓	
Helium		✓				✓			
Indium	✓	✓	✓	✓	✓	✓	✓	✓	
Iron (high-purity)						✓			
Iron Ore									✓
Lead							✓		✓
Limestone									
Lithium	✓	✓	✓	✓	✓	✓	✓	✓	✓
Magnesium	✓	✓	✓	✓	✓	✓	✓		
Manganese	✓	✓	✓	✓	✓	✓	✓		✓
Molybdenum			✓	✓	✓	✓	✓	✓	
Nickel	✓	✓	✓	✓	✓	✓	✓	✓	✓
Niobium	✓	✓	✓	✓	✓	✓	✓	✓	
Palladium				✓			✓		
Phosphate Rock		✓							
Phosphorus		✓			✓	✓		✓	
Platinum				✓			✓		
Platinum-Group Metals	✓	✓	✓		✓	✓		✓	✓
Potash						✓		✓	
Rare-Earth Elements			✓	✓	✓	✓	✓	✓	✓
- Heavy	✓	✓							
- Light	✓	✓							
Rhenium			✓	✓	✓		✓	✓	
Rubidium	✓		✓						
Ruthenium	✓								
Scandium	✓	✓			✓	✓			
Selenium			✓		✓		✓	✓	

(*) totals are as reported by each country and may not add as some countries itemise REEs and PGMs etc. separately, for instance, while others combine them. Source: 1) USA - US Geological Survey 2022, US Dept. of Energy 2023; 2) EU - EU 2023b, 2024; 3) Japan - Nakano 2021; 4) UK - BGS 2022; 5) Australia - Australian Government 2023, Australian Minister for Resources and Minister for Northern Australia 2023; 6) Canada - Canadian Government 2022, 2024; 7) India - Indian Government 2023; 8) South Korea - Yonhap 2023, IEA 2023c; 9) South Africa - Republic of South Africa 2022

It is possible that a more coordinated and cooperative global supply approach, perhaps under the auspices of the United Nations or a similar organisation, could lead to a more rapid resolution of global CRMs supply challenges.

Chinese dominance

Geopolitical risk has been heightened by China's dominance of the supply chain, and more recently by the conflicts in the Ukraine and the Middle East, and revolves around the need to ensure sufficient commodity supply to prevent or minimise disruption to the domestic economy, both in terms of ensuring CRMs supply for industry and the military (hence the number of specialty metals) and food supply (hence the inclusion of phosphates and potash for some countries). Europe, Japan and South Korea, major industrial powers with very limited domestic mineral production, are at the forefront of trying to secure supply. Notwithstanding attempts by other major industrial powers to limit Chinese influence through their own actions, China remains an aggressive investor in other countries through its Belt and Road Initiative (BRI). According to Nedopil (2024) China invested US$19.4bln in 2023 in BRI metals and mining initiatives, an increase of 158% on 2022 levels and the highest level since 2013. In addition, a further US$14.3bln was invested in technology, of which the lion's share was for batteries for electric vehicles (EVs), grid storage and other uses.

A rich history of supply concerns

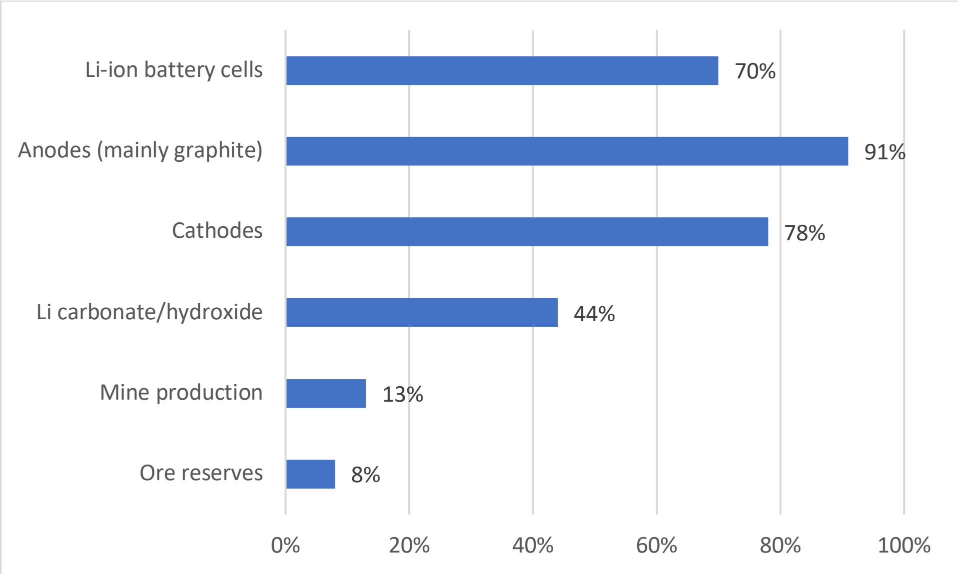
Geopolitics and raw material supply have, of course, been an issue for a very long time. In the USA, for example, there was talk of developing a national minerals plan soon after World War I (Chappell et al. 2007) leading, after World War II (when the USA required considerable materials for its military effort), to the creation of forerunners of the Defense Logistics Agency (2024). Other countries, like Japan, are even more reliant on imported raw materials. The parastatal Japan Organization for Metals and Energy Security (JOGMEC) was created in 2004 through the merger of the Metal Mining Agency of Japan and the Japan National Oil Corporation, predecessor companies of which were created in 1963 and 1967 respectively (JOGMEC 2024).

The challenge of multiple supply chains

Some of the challenges faced by resource-poor countries are the presence of multiple supply chains, each of which has its own supply/demand balance. There are essentially five different supply/demand equations for every commodity: ores, concentrates and matte; smelting and refining (including recycling); intermediate chemical products; constituent finished products (e.g. electric vehicle batteries) and final products (e.g. electric vehicles). We shall use what is surely the poster-child commodity in the challenge to meet Net Zero given its role in batteries for EVs and energy storage, lithium, as an example (we will use lithium to illustrate other points later as well). As can be seen in Figure 1, according to the Mining Journal (2022, quoting consultancy Benchmark Mineral Intelligence), China accounts for just 8% of the world's lithium reserves and 13% of mine production, but 44% of intermediate lithium carbonate and hydroxide production, 78% of global cathode output (as well as 91% of primarily graphite-based anodes) and 70% of the world's lithium-ion battery-cell production. And at the end-use level, China is also dominant. In its

Global EV Outlook 2024 report, the International Energy Agency (IEA) (2024b), notes the sale of almost 14mln electric cars worldwide in 2023, a 3.5mln or 35% increase over 2022 (to an 18% share of sales vs 14%). Of these 2023 sales, Chinese demand growth was forecast at 35% to reach 8.1mln units, 60% of the global total. For 2024, the IEA forecasts further growth in electric car sales to around 17mln units.

Figure 1 - China as a proportion of the global lithium market - greatest dominance upstream



Source: Mining Journal 2022 (after Benchmark Mineral Intelligence)

China is one of the world's largest producers, at the mine level, of many commodities, but it is its dominance further down the supply chain that is even more critical for supply in the rest of the world. This downstream dominance exists across the commodity spectrum, and for most CRMs. Just to illustrate the point, in October 2023, China announced that it would implement controls on the export of graphite from 1 December 2023. The country is the world's top graphite producer and exporter, and China refines more than 90% of the world's graphite which is used in virtually all anodes in EV batteries. The move follows the implementation of tighter export controls from 1 August 2023 on gallium and germanium, used in semi-conductor chips (Reuters 2023f). These developments were followed up by the publication in late June 2024 of new regulations issued by China's State Council aimed at protecting supplies of REEs in the name of national security. From 1 October 2024, the State Council will introduce a REEs product traceability information system overseeing the mining, smelting, separation, distribution and export/import of REEs products. The rules are aimed at controlling the industry and preventing illegal activity (Reuters 2024, Mining Journal 2024k).

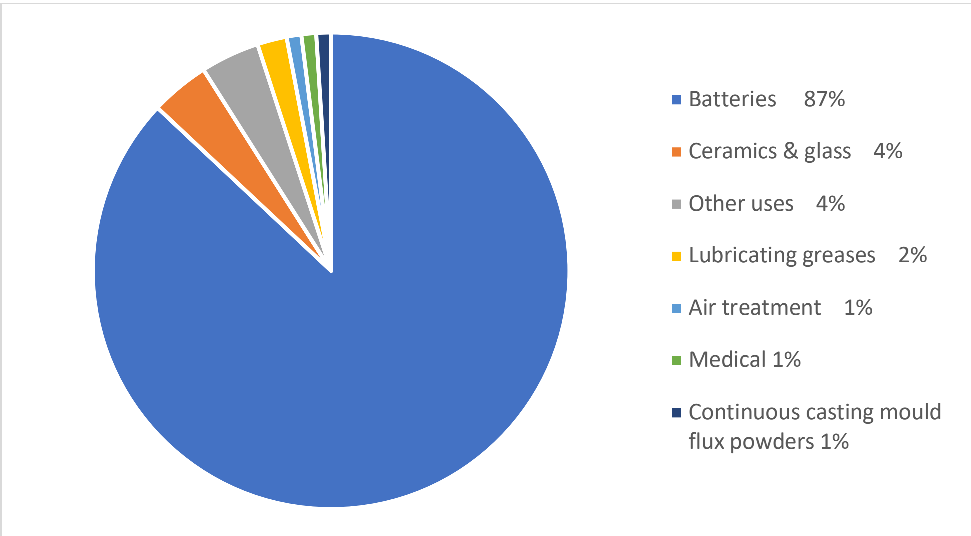
Demand can only grow at the rate of supply growth

Demand forecasts for CRMs, and especially those of significance in achieving Net Zero and other politically-set 'green' targets, inevitably chart from bottom left to top right; the only difference is in the gradient of demand growth forecast by different research groups. Most of these estimates, however, appear to ignore a basic home truth, and one of the fundamental laws of economics. Once excess inventory has been utilised, overall demand can only grow at the rate of overall supply. Latent or theoretical demand will then feed into commodity price growth as competition for supply grows, and may stimulate the search for additional supply, substitution (for other commodities) and micro sizing (reducing the commodity content per item). Inevitably, however, there is a lag and one of the key challenges the world faces is finding ways of reducing this time lag. This will be key if we expect to achieve all our 'green' targets.

Lithium: our example of demand growth

According to the Energy Institute's 2024 World Energy Review, lithium production grew globally from 30,400t in 2013 to 198,000t in 2023, a compound growth rate of c. 20.6%, and up 137% on 2020 levels. The International Energy Agency (2024c) estimates 2023 lithium production of 190,000t, 120,000t from hard rock deposits and 70,000t from brines. Figure 2 illustrates the significance of batteries which represent 87% of global lithium end-use, followed by ceramics and glass (4%), lubricating greases (2%), air treatment, continuous casting mould flux powders and medical uses (1% each) and other uses, 4% (US Geological Survey 2024a). Lithium-ion batteries are the predominant battery type used in electric vehicles and consumer electronics as well as grid-scale energy storage and other aerospace and military applications.

Figure 2 – Lithium: global end-use markets



Source: USGS 2024

Current consumption of lithium

The USGS (2024) estimates that global lithium consumption in 2023 was 180,000 tonnes (i.e. 958,100t of lithium carbonate equivalent or LCE, using a conversion ratio of 5.323), 27% above the revised 2022 figure of 142,000t. This would imply that approximately 833,600t LCE were used in the manufacture of lithium-ion batteries. The International Energy Agency forecast for total demand in 2023 (IEA 2024c) is slightly lower than the USGS estimate at 165,000t. Demand is fast-moving, and as a result estimates can vary greatly, and change rapidly. For example, the IEA (2024c) estimates annual capacity additions in 2023 of 35% for electric cars, 60% for wind generators, 85% for solar PV and 360% for electrolysers.

Lithium demand for electric vehicles

Rio Tinto (2023c) estimates that, based on 2021 data, the average EV battery size is 55kWh and requires c.40kg of LCE. The company also notes that battery size is expected to increase to 2030. Meanwhile Albemarle (2024b), quoting data from S&P Global Mobility, estimates the average global EV battery size was 50kWh in 2023, and will rise to 55kWh in 2024, 63kWh in 2027 and 68kWh in 2030. If one assumes the same LCE content ratio, this implies a global average of c.49kg of LCE per battery in 2030. Battery size differs significantly across different EV markets. The International Energy Agency (2023b) estimates that in 2022 average battery sizes for EVs ranged from just over 50kWh in China to c.80kWh in North America. The market is skewed in each region by the proportion of SUV, with larger batteries, sold in each market (high in North America) and small cars, with smaller batteries, sold (low in North America) and therefore the regional average will vary depending on car sales trends in different markets. Albemarle (2024b) estimates that around 680,000t LCE was used in EV batteries in 2023, rising to around 900,000t in 2024, c.1.76mln t in 2027 and c.2.55mln t by 2030. Other trends are regionally significant too. Two/three wheelers use smaller batteries than electric cars, while commercial vehicles (trucks and buses) use much larger batteries.

Lithium demand for storage batteries

Pumped-storage hydropower is the most widely used storage technology, but grid-scale storage capacity is growing rapidly and will become key in storing energy generated by renewable sources such as solar, wind or tidal power. By definition, these energy sources are highly variable and power generation is often related to uncontrollable elements such as weather, presenting challenges for utilities. Storage batteries allow this energy to be captured and used when needed. The IEA (2024a) estimates that global grid-scale storage capacity in 2021 was close to 160GW, most of which is used to provide daily electricity balancing. Total installed grid-scale battery storage capacity was close to 28GW by the end of 2022, with installations rising by over 75%, adding around 11GW of storage capacity. Almost all of this 28GW (over 80%) has been added in the last 6 years, and while still a small figure relative to total grid-scale storage capacity, battery capacity accounts for the majority of storage growth worldwide. The clearly predominant cathode chemistry (over 90% of the total) for storage was LFP (lithium ferrophosphate), with the balance primarily NMC (lithium-nickel-manganese–cobalt) batteries, according to the IEA (2021a). IRENA (2020) estimates that in 2019 energy storage batteries for EVs amounted to 200GWh, with a further 30GWh in stationary storage.

Future lithium consumption trends

Going forward, forecasting both supply and demand trends gets even more interesting. There are countless studies available, many considering different scenarios revolving around the world's ability to meet Net Zero and other 'green' targets, including the rate of penetration of EVs in different segments of the passenger and commercial vehicle markets, the growth in energy storage capacity and, of course, varying assumptions on the rate of change in growth and market penetration of alternative technologies. One example, from the World Bank (2020), looks at six different scenarios. Under the 2DS scenario (in which it assumes at least a 50% chance of limiting the average global temperature increase to 2oC by 2100), the World Bank forecasts a 450-500% increase in demand for graphite, lithium and cobalt from energy technologies in 2050 relative to 2018 production levels (with less spectacular but meaningful increases for several other metals). As technologies and applications evolve rapidly, forecasts can quickly become redundant, but the trend (if not the gradient) remains the same.

In recent analysis, S&P Global Market Intelligence (S&P) (2023b) estimates that light battery-electric vehicles (BEVs) will see annual production volumes rise from 8.8mln in 2022 to 44mln cars in 2030, representing 45% of the market. Between 2022 and 2030 S&P also forecasts that light passenger BEVs total energy produced will increase in size from 0.5TWh to 3.4TWh, and that the average battery pack size will increase from 60kWh/BEV to 79kWh/BEV. By 2034 production is forecast to reach c.60mln units, a 60% market share.

In global grid-connected battery electricity storage, S&P (2023b) sees installed capacity of c.200GW in 2025 (from essentially zero in 2015), with an additional c.300GW installed between 2025 to 2030, taking the total to c.500GW. That compares with just c.28GW capacity estimated by the IEA (2024a) in 2022. There is also the potential for the installation of much smaller units for commercial, industrial and residential use. S&P (2023b) estimates that in 2023, of total installed energy storage capacity, 71% was in front-of-meter (i.e. grid storage) applications, 21% in residential and 8% in commercial and industrial applications.

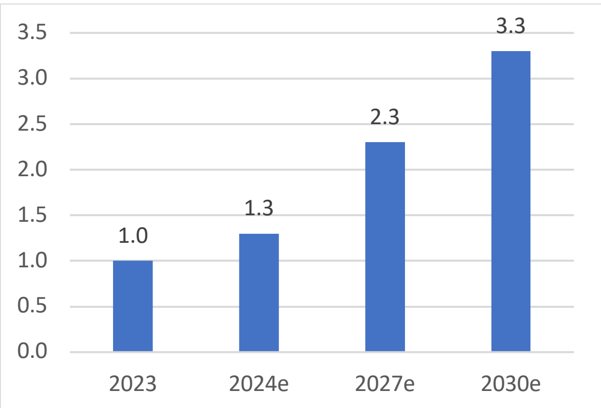
Alternative battery chemistries

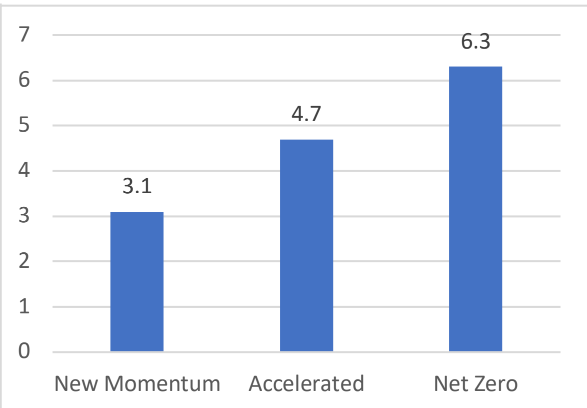
It is important to stress that not all of this EV and energy storage growth will rely on lithium-ion batteries, though it is likely to remain the dominant battery cathode material for the foreseeable future. Within lithium-ion cathodes, demand for different chemistries will grow at different rates. Between 2023 and 2030, S&P (2023b) forecasts a 4-fold increase of lithium-ion cathode demand, from c.1,000GWh to c.4,000GWh, with nickel-manganese-cobalt (NMC) and lithium–iron-phosphorous (LFP) batteries remaining the two dominant types, and manganese-rich and cobalt-free chemistries beginning to grow modestly in significance by 2030. In energy storage, Cleantechnica (2022) notes the three competing battery technologies in use; lead, lithium and vanadium redox flow. Their utilisation depends on multiple factors (applicable to EV batteries as well as energy storage). These include battery life, energy density (storage capacity), power density (rate of charge and discharge), cost and safety considerations.

Significant future shortfall?

Albemarle (2024b) currently estimates a 28% increase in lithium demand in 2024, from 1.0mln t LCE to 1.3mln t in 2024, rising to an estimated 2.3mln t in 2027 and 3.3mln t in 2030, a 17% CAGR, and 3.3-times 2023 levels (Figure 3). However, potential demand varies greatly based upon one's assumption of how quickly the world progresses in achieving 'green' targets, and as a result estimates of demand can vary greatly. For instance, in its 2023 Energy Outlook, British Petroleum (2023) forecasts 3.1mln t LCE demand in 2040 under its New Momentum scenario, 4.7mln t under its Accelerated scenario and 6.3mln t under its Net Zero scenario (Figure 4). All three scenarios require significant increases in lithium supply.

Fig. 3 – Albemarle's estimate of LCE demand (mln t) *Fig. 4 – BP's 2040 LCE demand scenarios (mln t)*





Source: Albemarle 2024b

Source: BP 2023

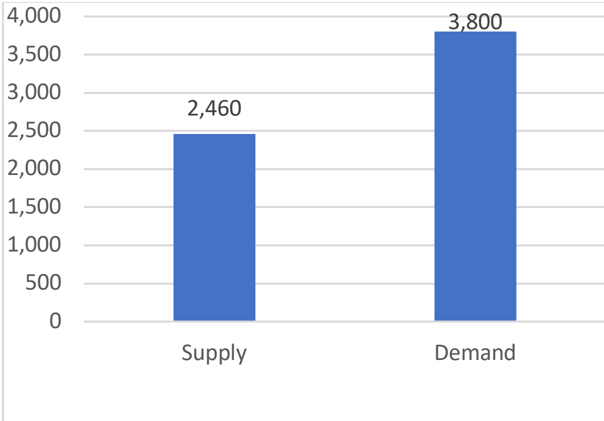
In May 2023, illustrated in Figure 5, the Chilean Copper Commission (Cochilco), quoted on Reuters newswires (2023c), forecast a lithium shortage with significant price hikes from 2031 and estimates that by 2035 annual global demand would reach 3.8mln t LCE, far exceeding its forecast supply of 2.46mln t

LCE, a supply deficit of 35% of demand. Inevitably, forecasts will differ based upon the assumptions made, but they all seem to suggest a significant long-term supply deficit.

Short-term market surplus

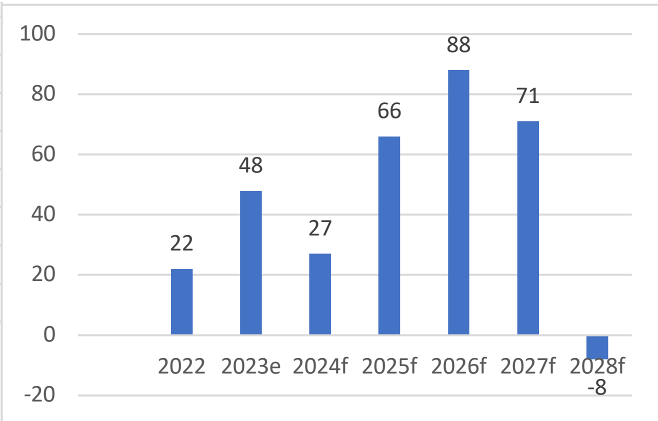
In the short-term, however, the path to supply deficit is less clear. Arcadium Lithium (2024) notes that 2023 saw increased inventory build through the energy supply chain, mainly in battery cells, and lower cathode production in H2 2023 led to rapidly declining lithium market prices (though we note that many sales contracts are long term agreements with less volatile pricing). Looking through supply chain destocking, EV/energy storage demand remained strong in 2023. Arcadium also notes that new lithium supply entered production in 2023, primarily higher cost material such as African spodumene and Chinese lepidolite output. In H1 2024 Arcadium notes that current (low) lithium prices are a major challenge for higher cost operations and a number of potential expansions, and higher cost lepidolite and unintegrated spodumene production is leaving the market while expansion activity is also slowing. Destocking is expected to continue in part thanks to extended downtime from Chinese cathode and cell producers around the Chinese New Year. The company notes that energy storage demand continues to grow, with balanced demand from carbonate and hydroxide-based battery technologies continuing to push demand for battery-grade lithium products.

Fig. 5 – Cochilco's estimate of LCE market 2035 (mln t)



Source: Reuters 2023c

Fig.6 – S&P's near-term LCE surplus (000t)



Source: S&P Global Market Intelligence 2024f

S&P Global Market Intelligence (2024a) estimates that global lithium production surged to 999,400t LCE in 2023 – a record high, and around 25% higher than 2022 levels of c.800,000t LCE – and forecasts a further 36% increase in 2024 to 1.36mln t LCE. In its latest assessment, S&P Global Market Intelligence (2024f) now believes that the market was in oversupply in 2023 by 48,000t due to rising lithium supply and slowing growth in EV sales and anticipates another surplus, 27,000t, this year with higher surpluses in subsequent years of 66,000t in 2025, 88,000t in 2026, 71,000t in 2027 before recording the first deficit since 2021 in 2028 (an 8,000t deficit) (Figure 6). The forecast of six successive years of surplus (2022 to 2027) is a very different outlook to the one envisaged up until recently by many commentators.

One of the latest substantial studies of the global CRMs market, with a clear focus on energy and achieving Net Zero, is by the International Energy Agency (2024c). The IEA looks at three scenarios – the Stated Policies Scenario (STEPS), based on today's governmental policies (50% probability of a 2.4°C temperature increase by 2100), the Announced Pledges Scenario (APS, 50% probability of a 1.7°C temperature increase by 2100) and the Net Zero Emissions Scenario (NZE, Net Zero CO_2 emissions by 2050 and a global temperature rise to 1.5°C above pre-industrial levels in 2100). Each scenario results in very different forecasts of CRMs demand. For instance, the IEA (2024c) sees 1.2mln t of lithium demand under STEPS, 1.6mln t under APS and 1.7mln t under NZE by 2050. Comparing the IEA's APS scenario on the demand side and its base case lithium raw material supply suggests that there is a potential supply shortfall of over 760,000t of lithium by 2040 unless we see a very substantial increase in raw material supply (IEA 2024c), as illustrated in Table 2.

Table 2 – Estimated lithium supply/demand under the IEA's Announced Pledges Scenario

000t Li	2021	2023	2030	2040	2050
Electric vehicles	35	83	398	1,124	1,353
Battery storage	2	9	44	79	99
Other uses	63	73	90	123	155
TOTAL LITHIUM DEMAND	101	165	531	1,326	1,607
Share of clean energy technologies	37%	56%	83%	91%	90%
Secondary supply & reuse	2	5	28	154	
Primary supply requirements	100	160	503	1,172	
Base case Li raw material supply:					
Australia	50	84	146	128	
China	17	34	103	103	
Chile	28	46	56	56	
Argentina	6	9	47	40	
Zimbabwe	2	9	34	34	
Canada	0	3	20	20	
Rest of the world	4	8	44	28	
TOTAL RAW MATERIAL LITHIUM SUPPLY	107	194	450	408	
Top 3 raw materials market share	89%	85%	68%	70%	
Secondary supply & reuse	2	5	28	154	
IMPLIED SURPLUS / (DEFICIT)	8	34	-53	-764	
Base case Li chemicals supply:					
China	70	114	213	215	
Chile	25	46	56	56	
Argentina	7	9	47	40	
Australia	0	6	30	30	
USA	0	1	17	18	
South Korea	0	0	4	5	
Rest of the world	0	0	6	6	
TOTAL LITHIUM CHEMICALS SUPPLY	102	176	373	370	
Top 3 chemicals market share	100%	96%	85%	84%	

Source: IEA (2024c), pages 125, 265, 266. Announced Pledges Scenario (APS) assumes that governments meet their climate-related commitments - assumes 50% probability of meeting a 1.7oC temperature rise in 2100. Raw materials cover extraction from hard rock, brines and clays. Chemicals covers first production of lithium carbonate, hydroxide, sulphates and chlorides, and excludes reprocessing.

The challenge of forecasting surplus or deficit in 'small' markets

Until December 2023, one of the world's largest lithium producers, Albemarle (2023c), had been forecasting total demand of 3.7mln t LCE in 2030, but mined supply of only 2.9mln t LCE, an 800,000t deficit representing over 20% of demand. However, in February 2024 Albemarle slashed its lithium demand estimate to 3.3mln t LCE (from the prior 3.7mln t estimate), an 11% reduction. Albemarle also reported 2023 demand of 1.0mln t versus its previous estimate of 1.2mln t, but none-the-less forecasts a 28% increase in demand in 2024 to 1.3mln t from the 2023 level (Albemarle 2024b). A key part of the challenge revolves around pricing and production costs. For instance, Albemarle (2024d) notes that lithium supply in 2030 is estimated at 2.7mln t LCE if prices remained at US$15,000/t in perpetuity - the year-end 2023 level (Albemarle 2024b) – but supply would jump to 3.2mln t if supply was unconstrained by pricing, a difference of 0.5mln t.

These considerations illustrate how difficult it is to forecast supply and demand for CRMs particularly with rapidly evolving technology and applications, even for major corporations deeply embedded within a particular commodity market.

Alternative viewpoints

It is worth adding that there are alternative viewpoints to both the potentially substantial longer-term shortfall in supply of CRMs and resulting impact on longer term pricing, including for lithium. For instance, FitchSolutions BMI (mining.com 2024h) believes that lithium prices have entered a 'new normal' period of stability, and now expect subdued pricing for the next decade. It cites the recent rapidly expanding supply (highlighted earlier) which, having pushed the market into surplus, means that lithium pricing is expected to remain below the peaks of 2022/2023 for at least 5 to 10 years, according to Fitch. FitchSolutions BMI now forecasts Chinese 99.5% lithium carbonate prices averaging US$15,500/t in 2024 and US$20,000/t in 2025 (compared with c. US$10,000/t currently, and a November 2022 peak of c. US$82,600/t) and lithium hydroxide monohydrate (56.5%) averaging US$14,000/t this year and US$20,500/t in 2025, compared with c. US$70,000/t in 2022.

Elsewhere, the Climate and Community Project (2023) has reviewed transportation in the United States and notes that projecting current demand for EVs out to 2050, lithium requirements for just the US EV market would be three-times current global lithium production. The study reports that the US could achieve zero emissions in transportation whilst limiting the amount of lithium mining required by reducing the dependency on cars in the US transportation system, reducing the size of EV batteries and maximising lithium recycling. Given the scale of the potential shortfall in supply for lithium and other CRMs we probably need to reduce dependency, reduce component size/content and maximise recycling across all CRMs and promote additional mining and processing if we are to meet the Net Zero challenge in a timely fashion.

Others (Gardiner et al. 2024) focus on the fact that some commodities may be only temporarily critical for short-term geopolitical reasons, whilst others may be 'structurally critical' leading to longer term efforts to increase supply, reduce demand and stimulate substitution. Different countries may therefore choose different routes to solving the issue for their domestic needs. The key point behind increasing the supply of a critical material to meet demand is to move it from the critical to the non-critical category. Gardiner et al. (2024) highlight five routes to non-criticality for lithium by 2035 (that could potentially be applied to other critical materials): business as usual (increases in, primarily, hard-rock lithium supply); clays coming onstream (augmenting hard-rock and salar supply); everything plus recycling (oilfield and geothermal brines, as well as clays, hardrock, salar and commercialised recycling); shift away from lithium (supply shortages and high prices stimulate alternative battery technologies); and, lastly, a lithium 'black swan' event (war, pandemics, technological paradigm shift etc.). As soon as a commodity moves from critical (shortage of supply, surging demand, high pricing potential) to non-critical (abundant supply or oversupply, alternative applications or obvious substitution, low pricing tension) exploration shifts to other commodities that are more critical at that point-in-time, and we begin the traditional commodity supply, demand and pricing cycle.

While 'black swan' events are, by definition, not predictable, an indication of their potential impact is outlined in a recent US Geological Survey report (2024b) which considers the impact of earthquakes on global copper and rhenium supply. The USGS concludes that global copper mining supply could be impacted by 0.3-1.1% (US$315-1,290mln of lost revenue), with disruption of 1.8-4.0% of copper smelter production (US$1.92-4.33bln of lost revenue), 1.5-3.3% of copper refining output (US$2.06-4.52bln of lost revenue) and 0.32-1.32% of annual rhenium production capacity (US$337,000-1.40mln of lost revenue).

Development to production: the challenge

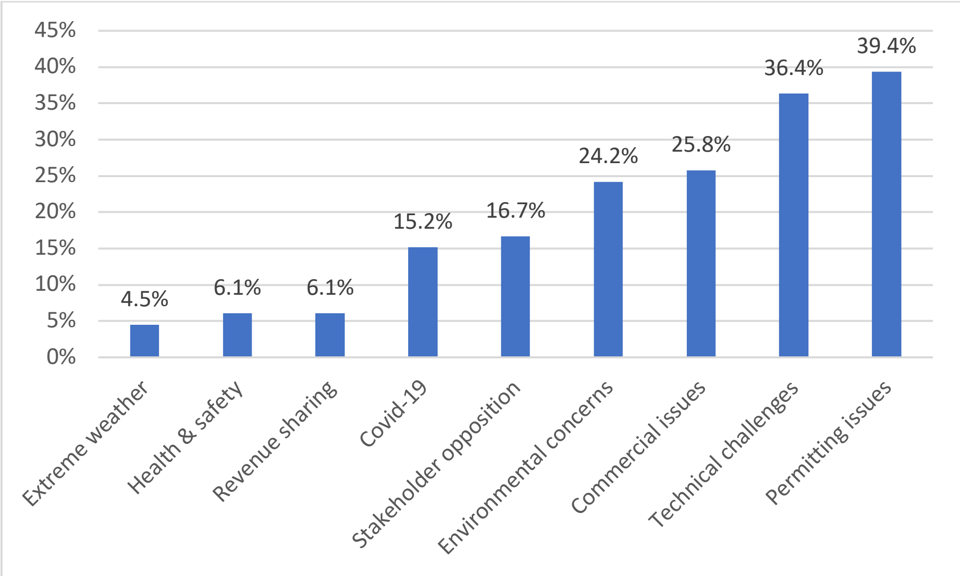
Most estimates suggest a growing supply deficit for most critical materials, not just lithium. But while potential demand may substantially beat supply, as noted before, actual consumption can only grow at the rate of growth of actual supply, and that means that we may be heading for a substantial supply deficit for almost all critical materials in the medium to long-term. Inevitably commodity prices will rise and this will self-regulate demand to some extent. But at the end-of-the-day, we need to see greater cooperation across the supply chain; active and positive collaboration between national and local governments, mining companies, local communities and financial markets if we are to fast-track the world to a 'green' Net Zero future.

Long lead times for mining projects

There is no guarantee that an exploration programme will prove-up an economically viable project. The challenge is enormous. According to the Prospectors and Developers Association of Canada (2024), of 10,000 identified mineral prospects, only about 10% (1,000) will lead to a drilling programme and just 0.01% (1 in 10,000) will lead to a new mine. Of course, economic viability can change; as commodity prices increase, a previously uneconomic mineralised zone or orebody may become economically viable. Pricing, however, is only one aspect in the delay of a project. Others include environmental issues, local opposition, permitting and planning delays, changes to royalty or tax regimes (particularly if unexpected), local or national political indifference and so on. Between discovery and production there are frequently long delays. As Figure 7 illustrates, a significant number of concurrent and sequential workflows, all of which require cooperation and approval by other stakeholders, are needed in the project appraisal and development stages of a mining project. As a result there are frequently significant delays in mine development. Schade (2014) notes that of c.3,500 non-ferrous deposits found between 1950-2013, the average delay between discovery and start-up was 12.4 years. In 2020, Hinde (2020) noted a 28.7-year average delay between development and production of the largest 45 mines (copper, gold, nickel) discovered around the world with start-ups between 2010-19. Meanwhile, in 2023, numbers from S&P (2023b) covering 127 gold, copper, nickel, silver and zinc mines identified a 15.7-year average lead time between discovery to production. More recently (March 2024), the World Bank quoted a discovery-to-production time lag of 14.9 years (Mining Journal 2024d), while the most recent estimate (May 2024, Mining Journal 2024j), quoting S&P Global Commodity Insights, notes that the average time from discovery to production is now 16.3 years, including a 12-year exploration and study phase. Between 2005 and 2009 the average lead time was quoted as 13 years, increasing to 18 years between 2020 and 2023 due to delays in financing and permitting. S&P Global Market Intelligence also note the wide variation geographically, with projects in Zambia taking 34 years on average from first discovery to production, and long time lags in key mining (and demand) jurisdictions like the USA (29 years), Canada (27 years) and Australia (20 years). Contasting this, the average lead time in Laos, the Democratic Republic of the Congo and Spain is 15 years or less (Mining Journal 2024n). These variations shape the allocation of exploration spending geographically. The time-lag between discovery and production will constantly change, but at the moment it is clearly much too long if we are to meet our 'green' targets.

Ideally, the time between discovery and production needs to be brought down to between 5 and 10 years. Sustainability consultants ERM (2024), concur with this and note that their analysis of over 100 critical minerals projects (primarily cobalt, copper, graphite, lithium, manganese, nickel, Rare Earths, or zinc) show that between 2017 and 2023 almost 60% of projects sustained pre-production delays of a few months to up to several years. 80% of these projects were delays by permitting issues, environmental concerns or stakeholder opposition while 62% also suffered from technical challenges and commercial issues (Figure 8).

Figure 8 – Causes of delay to critical minerals projects (2017-2023) (% of delayed projects)



Source: ERM 2024

Increasing focus on juniors and increasing discovery costs

The length-of-time between discovery and production is only one of the many challenges the industry is facing. As noted by Schodde (2023), 63% of all discoveries in the Western World between 2012-2021 were by junior exploration companies, and between 2018-2021 this has averaged around 85%. However, the average cost of discovery in the Western World has risen four-fold in real terms in the last two decades to US$240mln (Schodde 2023). Juniors are struggling to finance exploration programmes, and as a result, the number and size of discoveries are declining in most mining jurisdictions. We need to find better ways to finance junior, entrepreneurial, exploration companies and find a way to reduce the red-tape that stretches these companies' financial and technical resources.

Future sources of critical raw materials' supply

We can expect to see a shift in the upstream and downstream balance of production, as volumes from new or recent discoveries are eventually developed, with greenfields production volumes ultimately exceeding brownfields expansion potential. In lithium, S&P (2023b) expects Australia to remain the largest source of raw material supply, but with increasing growth in Latin America (Argentina, Chile and Brazil in particular), in North America (Canada especially, but also the USA and Mexico) as well as in Africa. As an example, Cochilco (Reuters 2023c) estimates that Argentinian lithium output will increase from 28,000t LCE in 2021 to 415,000t by 2035. Further downstream intermediate production volumes will also increase and it is reasonable to assume that Chinese market share, though remaining significant, will decline as other regions (albeit slowly) begin to start or increase production of lithium carbonate and hydroxide. The rate at which this happens, however, will be a function of the financing and political issues identified later.

New ore deposits and sources

We return to lithium to illustrate the potential for new deposits and sources. There is no geological shortage of lithium; the USGS (2024a) estimates global reserves of 28mln t (which is sufficient for over 150 years of production at current production rates) and resources of 105mln t. At present around 60% of the world's lithium is sourced from hard rock deposits, primarily pegmatites, with Australia being by far the largest producer (IRENA 2022). The mineral spodumene makes up the majority of hard-rock production and is typically processed and sold as a 6% Li_2O concentrate, but other commercial or near-commercial minerals exist, including lepidolite, petalite and zinnwaldite. The balance of lithium production is primarily from salar brines, in particular from Chile and Argentina. Increasingly, however, new sources of lithium are likely to come into play, as technology develops economically viable extraction methods. These include lithium clay deposits such as the claystones in the McDermitt Caldera in Nevada and Wyoming, oilfield brines, where lithium-enriched brines are extracted with oil and gas (such as in Alberta), geothermal brines (Cornwall, England and Upper Rhine Valley, Germany) and lithium zeolites (jadarite) found in Serbia.

New exploration, mining and processing technologies

Over the years, various technological advances that have boosted the mining industry, and this trend is likely to continue and potentially accelerate as the world attempts to satisfy future commodity demand. While exploration and processing technological advances add new ways to find additional ore deposits and to process ores that could not be economically processed before, so adding to the extractable resource base, advances in mining methods tend to be more about improving efficiency, controlling or lowering costs and improving the 'green' credentials of mining. Innovation in exploration, mining and mineral processing must be considered against the trend of declining ore grades for most commodities - copper head grades are down 7.6% between 2010 and 2022, for instance (S&P Global Market Intelligence 2023e) - requiring the discovery, mining and processing of ever-increasing tonnages of ore just to sustain current demand levels, let alone allow for increasing demand.

Exploration

In exploration, we have seen numerous advances in geophysical techniques. One good example is the discovery of several gold-copper deposits in recent years in the Paterson Province of Western Australia. The Telfer gold-copper and Nifty copper mines were discovered in 1970 and 1981 respectively thanks to the presence of surface outcrops, but most of the Paterson Province is covered by sands of the Great Sandy Desert.

Advances in geophysics allowed Greatland Gold to identify the Havieron gold deposit in 2018, under 420m of post-mineralisation cover. Although the deposit was first identified and drilled by Newcrest between 1991 and 2003, it later dropped the project. Greatland (Greatland Gold 2016) acquired the project in 2016 and, as corroborated by a number of press releases containing results from its two drilling campaigns in 2018, made a major gold-copper discovery at Havieron in 2018. Credit for the initial targeting, however, must go to forward modelling of detailed aeromagnetic data and detailed ground gravity data which penetrated and allowed accurate interpretation of mineralisation at depth, assisted by MMI (Mobile Metal Ion) geochemical sand/soil sampling (Greatland Gold 2018, Hanneson and Baxter 2022). Newcrest farmed back into the project in 2019 (Greatland Gold 2020). The project is progressing; development work at the mine now exceeds 3,060 metres and an updated mineral resource was released in December 2023, which highlighted a 29% increase to 8.4mln oz AuEq (7.0Moz gold and 275,000t copper) (Greatland Gold 2024a). Following the acquisition of Newcrest by Newmont in November 2023 (Newmont 2023), in February 2024 Newmont announced its intention to divest the Telfer mine and Havieron project (Newmont 2024). Ironically, Newcrest was formerly Newmont's Australian subsidiary and was listed on the Australian Stock Exchange in 1987 (Canberra Times 1987). In September 2024, Greatland Gold announced that it had a binding agreement to acquire Telfer and Newmont's 70% stake in Haverion (taking Greatland to 100% ownership) for up to US$475mln before adjustments (Greatland Gold 2024b).

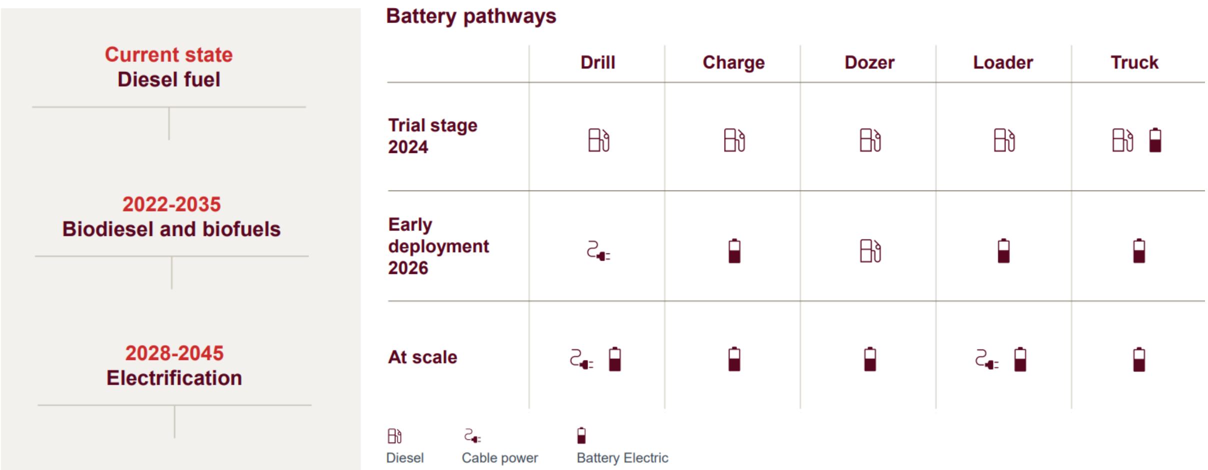
In the last decade numerous other operators have used similar exploration techniques to identify gold-copper deposits under sand cover in the Paterson Province. These include Antipa Minerals, which, in 2022, announced total mineral resources at Minyari Dome of 1.8Moz Au (plus Cu, Ag, and Co) and completed a Scoping Study for a 170,000ozpa gold mine (plus by-products). Antipa has also had success at other targets including its Citadel JV with Rio Tinto, whilst the latter has also reported a mineral resource at its own Winu project of 721mln t grading 0.40% Cu, 0.34g/t Au and 2.21g/t Ag (Antipa Minerals 2022a & b and 2024, Rio Tinto 2024b).

New exploration techniques

Okada (2022) provides a useful review of breakthrough technologies in mineral technology and highlights areas that may provide breakthroughs in exploration technology soon. These include improvements in economic efficiency using unmanned and automated applications (e.g. unmanned aerial vehicles and automatic spectroscopic scanning of drillcores), higher accessing capability (e.g. improvements in airborne geophysical techniques) and higher efficiency and productivity (e.g. automatic data processing by neural networks/deep learning) and lower implementation costs (use of drones vs manned airborne exploration). Other suggestions include determining the induced polarisation (IP) effect on sulphide minerals associated with mineralisation through spectral IP, the characterisation of the deep underground via enhancement of superconducting quantum interference device (SQUID)-based time-domain electromagnetics (TDEM) and the geophysical removal of the effects of conductive deeply-weathered overburden and magnetic mineral-rich younger volcanics, and finally, the use of hyperspectral mapping with high spatial resolution.

We are also likely to see further big-leap ground-breaking advances in exploration techniques. For instance, in December 2023 NASA (2023) produced the first global maps from its Earth Surface Mineral Dust Source Investigation programme. The project involves an imaging spectrometer, launched to the International Space Station in 2022. NASA claims that the programme can cover huge areas of desert that would be impossible for on-the-ground or airborne geophysical exploration to cover, while effectively achieving the same degree of detail through monitoring how minerals reflect and absorb light. 10 key minerals were researched, including hematite, goethite and kaolinite. The news release notes the potential to locate sources of phosphorus, calcium and potassium (i.e. fertiliser minerals) and also sources of Rare Earth Elements and lithium-bearing minerals. This programme could have potentially huge ramifications.

Figure 9 - Fleet electrification will require time and technology breakthroughs



Source: Rio Tinto 2022b

Mining

The mining industry has not done a great job at marketing itself as an innovative and 'greening' industry. Sanchez and Hartlieb (2020) review some of the new innovative technological drivers in the mining industry, particularly with regards to digital transformation. Not all mining companies have the financial and technical resources of the majors, but this example, from Rio Tinto, illustrates what is possible. Rio's Pilbara iron ore business in Western Australia consists of 17 iron ore mines and four independent shipping terminals in two ports. Mines and terminals are connected by a rail network, almost 2,000km long, which is Australia's largest privately-owned and operated rail system and is the world's first automated heavy-haul rail network, called AutoHaul (Rio Tinto 2024a). Rio's newest Pilbara iron ore mine, Gudai-Darri, opened in mid-2022. The mine utilises the autonomous (driverless) trucks, trains and drills already used across Rio's Pilbara network, but also incorporates the world's first autonomous water carts (for dust suppression). Rio Tinto (2022a) anticipates that once development is complete the world's first operational deployment of Caterpillar 793 zero-emissions autonomous haul trucks will be at Gudai-Darri. But as Rio notes, and as illustrated in Figure 9, fleet electrification will require time and technology breakthroughs. Gudai-Darri will also have a robotic ore sampling laboratory, robotics in the heavy mobile equipment warehouse, a solar farm, a digital (to scale) 3-D model to aid training, planning and operation and paperless field mobility (with team members using tablets).

Underground challenges

These examples are illustrations, primarily, of surface mining innovation, but as underground mines go deeper, additional challenges come to the fore here too, including, as outlined by Cai et al. (2021), high in-situ stress, lithology deterioration, the impact of high temperatures and challenges with deep hoisting. These issues have become increasingly relevant as mines go deeper – the deepest, the Mponeng gold mine in South Africa, is currently 3.9km deep – and deep South African gold mines have, for some time, been struggling with rockbursts, earth tremors and excessive heat. If we are to extract otherwise economically viable ore zones at increasing depths further, substantial, research will be required to predict, minimise and control the impact of rockbursts, improve support and cooling and hoisting technology, develop precision-cutting mining techniques (high pressure water jets, laser and plasma), improve integrated mining and underground processing of ores, reduce waste and develop wasteless production, develop deep-level in-situ solution mining, and advance intelligent unmanned mining (Cai et al. 2021).

AI and robotics

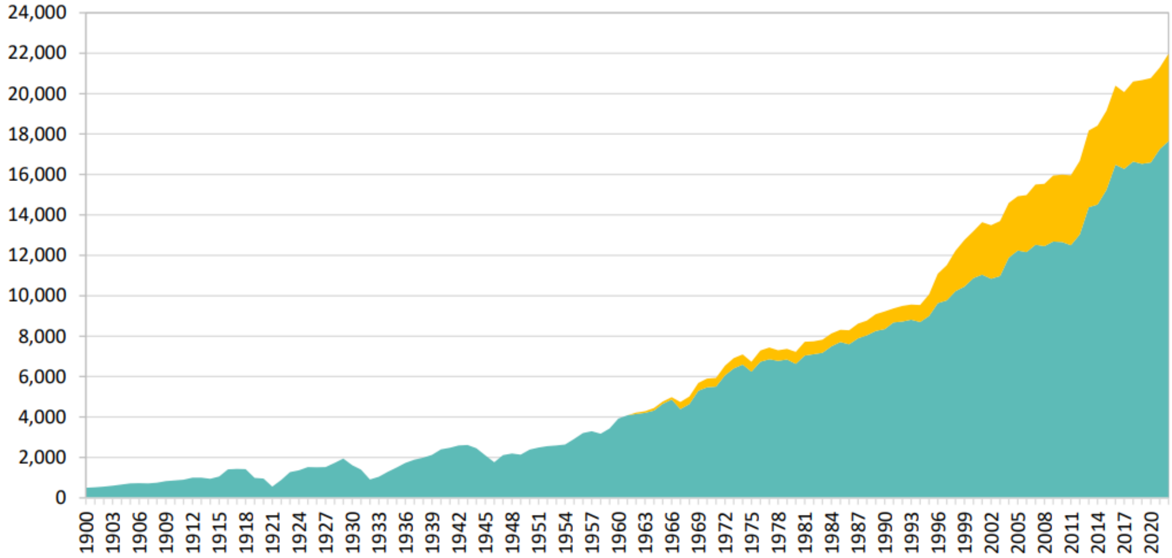
On a broader scale there is growing use, particularly amongst the largest technology-facing mining companies with the deepest pockets, of digitisation and the use of artificial intelligence (AI) and advanced analytics across the mining value chain. Mining Journal (2020) notes that this may be in project planning and design, with up to a 15% improvement in NPV, to optimisation of exploration and improvements in equipment utilisation, recoveries and productivity in mining and processing, with gains of anything up to 30%. More recently, Harambasic (2023) notes AI applications in exploration (including surveying and 3-D mapping), material management (ore, waste and water), autonomous and remotely operated equipment and in maintenance, performance and safety. McKinsey (2024) notes the potential for generative artificial intelligence to aid mining companies in managing their fleets of complex and widely distributed machines with libraries of maintenance manuals, historical work orders, procedures, tooling inventories and parts databases. There could be several other uses, including speeding up and assisting in the processing, interpolating and interpreting sets of exploration data.

Robotic solutions are also being assessed and may become economically viable in the future. One example is Offworld AI (2024) which talks about providing autonomous mining solutions both on Earth and the moon, via its Swarm Robotic Mining Excavation Squad which includes surveyor, excavator, collector, and hauler robots, while its Energy Squad adds battery swapping and charging station units to the team.

Processing

There have been constant advances in processing technology over the last 100 years which have allowed for the economic recovery of metals from lower and lower grade ores, and from material that it was previously impossible to extract the metal from economically. Bioleaching, for instance, is a natural process, where water, air and microorganisms (bacteria and archaea) catalyse the oxidation of sulphide minerals. According to Dresher (2004), this process was noticed in ancient times, but first commercialised in the late 1950s at the Bingham Canyon copper mine, and is now used commercially to process not only copper ores, but also nickel, cobalt, zinc and uranium, whilst biooxidation (the oxidation of sulphide minerals that may be associated with but not part of the mineral of economic interest) is used in gold processing and coal sulphurisation. Dresher (2001) notes that further advances in copper extraction were developed from the leaching of near-surface oxide ores (and the reworking of oxidised sulphide waste) with sulphuric acid, a process known as solvent extraction/electowinning (SX/EW). It was first used commercially in 1959, and initially used on a large scale in 1968 before becoming more widely used from the mid-1980s. In 2022, the International Copper Study Group (2023), as illustrated in Figure 10, notes that copper production from SX/EW and bioleaching was 4.3mln t, or 19.5% of global mine production. Other major historical technological advances in mineral processing include the widespread use of pressure leaching and pressure oxidation for the treatment of certain nickel, zinc and gold ores. Most leading mining companies endeavour to develop and further refine their own processing steps to improve recoveries and treat ‘difficult’ ores, but some companies, like Glencore, make a business of selling processing technology to third-parties. It’s Glencore Technology (2024) subsidiary highlights a number of these including IsaSmelt (pyrometallurgy), the Albion Process (hydrometallurgical leaching), IsaMill (horizontal milling), ISA KIDD (copper electrowinning/electrorefining) and the Jameson cell (flotation). Glencore Technology has published over 185 technical papers relating to its technology. Over 500 installations globally, and almost all of the largest mining companies in the world, use technology developed by Glencore Technology and predecessor companies (like Mount Isa Mines).

Figure 10 - Increasing volumes of SX/EW copper mine production (000t)



Source: International Copper Study Group 2023

Future technology in lithium processing

Further advances in technology can be expected. For instance, turning back to lithium, we continue to see advances in Direct Lithium Extraction (DLE) from unconventional non-salar geothermal and oilfield brines, as well as conventional salar brines. Eramet and Tsingshan have just started Phase 1 production at their Centario salar project in Argentina (Eramet 2024). Relative to conventional brine extraction, DLE has the potential to eliminate or reduce the need for evaporation ponds (smaller land area required; outcomes not weather dependent), decrease production times (to days not months), increase recoveries (from 20-50% to 80-90%), improve ESG/sustainability (lower fresh water and energy demand), lower operating costs (reduced reagent usage) and increased product purity (McKinsey 2022, Goldman Sachs 2023). The only currently commercially viable DLE technology is absorption, but other technologies are undergoing pre-commercial testing, including ion exchange, solvent extraction, membrane separation and electrochemical separation.

Other development work is being undertaken on Direct Lithium to Product (DLP), that seeks to add only lithium metal to polymer. The lithium is then removed to an electrolyser tube and converted into a final lithium product, according to McKinsey (2022). The key lithium mineral is spodumene. A spodumene processing plant seeks to upgrade run-of-mine ore grading 1-2% Li2O to a spodumene concentrate (SC6) containing at least 6% and up to 7% Li2O for lithium carbonate (i.e. battery-grade) material. Other industries, like ceramics, require higher grade (7.6% Li2O) spodumene concentrate with a low iron content (SGS Mineral Services 2010). Further advances in lithium technology may allow the production of greater volumes of spodumene Direct Shipping Ore (DSO).

Technological advances may also allow for increasing economic development of orebodies containing other lithium minerals like lepidolite, petalite, amblygonite, and eucryptite, and the first commercial production of lithium from zinnwaldite, such as from the Zinnwald/Cínovec deposit straddling the German/Czech border, clay deposits such as those found in Nevada and jadarite at Jadar (Serbia).

One good example here, is the processing of zinnwaldite. Zinnwald Lithium and European Metals Holdings manage, respectively, the German (Zinnwald) and Czech (Cinovec) halves of the Zinnwald/Cinovec lithium pegmatite deposit. Lithium has not, historically, been recovered commercially from zinnwaldite mica deposits, and both companies are planning to use calcination with gypsum and limestone in rotary kilns (Zinnwald Lithium 2023, European Metal Holdings 2022). However, research suggests that other processing methods may prove commercially viable, such as carbonation roasting (Choubey et al. 2016) or direct carbonation via autoclaving (Martin et al. 2017).

Management skill-sets and geometallurgy

An issue that we touch on later is the need to attract new, young, entrants into the mining industry. But we also have a labour challenge in management. Traditionally, graduate labour in the mining industry followed three key pillars – geology, mining engineering or metallurgy/mineral processing. We do not have enough skilled workers moving up the management ladder bringing newer approaches to mining with them, particularly in terms of cross-disciplinary applications such as geometallurgy. Geometallurgy has been defined by Dominy et al. (2018) as 'an interdisciplinary activity that integrates geology, mining/geotechnical engineering, metallurgy, mineral economics, and geoenvironmental parameters to maximise project economic value, reduce risk, build resilience and demonstrate good management of the resource'.

Bamber and White (2023/24) provide some good examples of geometallurgy in action. One of these is Teck's Red Dog zinc mine in Alaska, which was originally commissioned to exploit extremely high grade zinc ores in the sulphide zone. Over the years, grade declined and ores became more complex, and included siliceous zones (generally harder and lower grade), baritic zones (low grade but with a lower work index, so lower processing cost and higher throughput) and high-iron (pyrite) zones (recovery challenges). Through improved definition and characterisation of the geometallurgical units, re-planning was based on this, rather than on grade. Cashflow was enhanced by focusing on softer lower grade barite zones rather than the higher grade but harder siliceous zones (which would have meant lower throughput and higher operating cost). High grade but lower recovery iron-rich material was generally deferred in the revised mine plan in favour of lower grade but higher recovery material.

There is nothing particularly new about geometallurgy. In reference to the crossover of geology and metallurgy, the phase geometallurgy was apparently first coined in 1968, but its origins can be traced back at least to 1556 and Georgius Agricola's De re metallica, and the concept is no doubt much older (Frenzel et al. 2023). While there is nothing especially unique about different disciplines cooperating to solve problems together, it is still the case that many mining operations focus on the mantra of grade or tonnage, when more widespread use of geometallurgical techniques could enhance a project net present value (NPV) by perhaps treating lower grade but softer ore, with a lower work index and therefore lower operating costs. With greater use of artificial intelligence, data mining and a younger management, it is possible that in the future we will see better use of orebodies to maximise raw material production; this is one of the hidden aspects of enhancing output to assist in satisfying supply shortfalls of critical and other raw materials over the next few decades.

New sources of raw materials

There are four exciting areas of future potential CRMs supply that could have meaningful impacts on commodity supply, but all three come with huge ESG challenges. On land, ice melt is making available land that has never been subject to mineral exploration, leading to the potential for bonanza high grade discoveries offset, to some extent, by the impact of subsidence from thawing permafrost. Phytofarming – the commercial extraction of metals from plants – is also advancing as a technology that could augment mine production and revenues and reduce soil pollution. Under the sea, which covers over twice the area of the planet's exposed land mass, the potential is huge, matched by the unknown environmental damage that could result from deep-sea mineral exploitation. And in space, the potential, again, is huge, but significant cost and technology challenges still need to be overcome.

Ice melt expands terrestrial exploration potential

One of the consequences of global warming is that ice melt is making more of the planet accessible to exploration. Much of the literature is focused on the Arctic, perhaps because of its proximity to some of the world's leading natural resource producers, Canada, the USA (Alaska), Russia and Scandinavia, and primarily because of the significant Arctic petroleum output of these countries. On the academic front, the focus is principally on socio-environmental elements (for example, Tolvanen et al. 2019, and Hanaček et al. 2022) and the impact on the environment and on indigenous people such as the Sámi of northern Scandinavia and Russia's Kola Peninsula.

In terms of mineral exploration, one of the areas that has attracted the most popular interest revolves around ice melt in Greenland, and the impact that is having on making land available for exploration. In term of newsworthiness, it helps having billionaires like Bill Gates, Jeff Bezos and Michael Bloomberg involved (Energy Monitor 2023). They have all invested in KoBold Metals which has an exploration joint venture with 80 Mile (formerly known as Bluejay Mining) in Greenland. Christiansen (2022) has reviewed the history of mineral exploration in Greenland and reviewed the next era of exploration (though without mention of the impact of receding ice). While there has been some historical mining on Greenland (for instance, the Black Angel zinc-lead-silver mine which operated between 1973 and 1990), operations have been limited and hampered by ice cover and general logistical challenges. None-the-less, there are several CRM projects undergoing assessment, all of which (because of ice cover elsewhere) have coastal or near-coastal locations. Amongst others, they include deposits containing REEs, graphite, PGMs, nickel, copper, cobalt, molybdenum, tantalum, niobium and ilmenite.

Not just an Arctic story

But you don't need to be as far north as the Arctic to see the effects of ice recession on the potential for mineral deposit discovery. Large parts of northern Canada, Alaska, Scandinavia and Russia are witnessing rapidly receding ice. Take the Golden Triangle, in northwestern British Columbia, stretching, broadly, between Stikine, Cassiar and Atlin (the sites of three 19th century gold rushes). The region was home to some of the highest grade gold-silver mines ever discovered in Canada and the world, and was a key gold mining district from 1918, when the Premier gold mine opened, to 2008, when the Eskay Creek mine closed (Visual Capitalist 2016, Skeena Resources 2023). In the last decade, mineral exploration has picked up, and is now booming as exploration companies access land that was previously ice-covered and inaccessible to exploration (Investing News Network, 2021).

There has been very little, if any, research on the impact of ice melt on mineral resource availability, but the ramifications are huge. Many of the areas where ice is receding have been under ice cover for thousands of years and have never undergone exploration of any sort. So quite apart from the increase in land area available for exploration, we have the potential, with first-mover exploration advantage, for surface or near-surface bonanza high-grade discoveries that elsewhere would have been discovered and exploited by previous eras of miners from ancient times, through the Middle Ages to the intrepid explorers of the 19th century. Exploration geologists will be able to take till samples, and utilise striation mapping and other ice flow directional indicators to determine source locations. The potential for meaningful mineral discoveries is huge.

The downside – permafrost thawing and subsidence

Unfortunately, there is a downside to the unintended bonanza that ice melt may give us. Across large areas of northern North America, Scandinavia and Russia ice roads in winter will see shortened life spans and, more significantly, we will see the impact of thawing permafrost through subsidence disrupting infrastructure, including some potentially significant impacts on petroleum and mining infrastructure and the communities that serve them. One recent graphic example was the diesel oil spill at Norilsk Nickel in Russia in 2020, when a tank collapsed as a result, it is thought, of thawing permafrost (The Arctic Institute 2020).

Phytomining

Phytofarming is defined as 'the process of using plants capable of bio-extracting metals from soil in order to explore them economically' (Kikis et al. 2024). This could have the double benefit of leading to the recovery of metals and the remediation of land with elevated levels of metals, thus reducing soil pollution levels. The technique could potentially be used on the tailings and waste dumps of former mines, aiding long-term land reclamation. Recognition that certain plants are metallophytes or hyperaccumulators of certain metals is not a new phenomenon, but in recent years there has been a growing awareness of the economic potential of phytofarming (Tomorrow's World Today 2024). Kikis et al. (2024) note that a number of different plant species have the ability to concentrate different metals, including nickel, cobalt, cadmium, zinc, manganese, selenium, thallium as well as gold, silver and PGMs. Companies like Viridian Resources, Metalplant and Econick (company websites (6) 2024) are primarily focusing on nickel recovery.

Viridian describes the simple process of harvesting, baling, drying and ashing the hay-like crop to produce a metal-rich concentrate as a high-grade feed to existing smelter/refineries and for direct marketing. Viridian notes that nickel laterites are the most appropriate resource base and that resources with nickel grades of as low as 0.05-1.0% nickel could be utilised. 1,000ha could yield 15,000-25,000t of biomass annually which, at 2% nickel, would capture 250-550t of nickel and c.15,000MWh of electricity (25,000t biomass, 6,500Btu/lb). Veridian claims a 450tpa nickel project would, at US$6.00/lb Ni, yield US$4mln net revenue from nickel and a further US$1mln from power credits.

While this process is unlikely to yield large tonnages of metals, it could add to production and revenues at existing mines while reducing ongoing pollution risks, and help to clean historical minesite pollution levels.

Deep-sea mining

Two areas of potentially great significance for future raw material supply are the deep sea and space. Both may sound far-fetched and of course have huge environmental implications, but a lot of work has been undertaken in both areas. This is no longer in the realms of science fiction, but it is certainly controversial.

With 71% of the Earth covered by water, and 96.5% of this water being contained in oceans, seas and bays, 68.5% of the world's surface is covered by seawater according to the USGS (2019). It is little wonder then, that as terrestrial resources become harder to find, humans are beginning to focus on extracting minerals from the deep sea. There are essentially three types of deep-sea deposits, with three types of extraction planned, according to the Deep Sea Conservation Coalition (2024). The abyssal plains contain vast quantities of mineralised nodules; some are manganese-rich while others are polymetallic (adding to their attraction from a commodity extraction perspective), seamounts may have mineralised crusts (for cobalt in particular), while hydrothermal vents exude polymetallic sulphides. The locales of all three types of mineralisation play host to complex ecosystems, and it is not clear at present what ecological damage could be done by mineral extraction.

The Clarion Clipperton Fracture Zone

One of the first areas for which deep-sea exploitation licences may be sought, is in the Clarion Clipperton Fracture Zone (CCZ) in the Pacific, between Mexico and Hawaii, where polymetallic nodules containing nickel, copper, manganese and cobalt are found at depths of 4-6km. Proponents of deep-sea mining, like The Metals Company (2023), have produced impressive claims for the need for deep sea metals and the environmental safety of their ventures, while various environmental groups like Deep Seas Conservation Coalition and Deep Sea Mining Campaign have made equally impressive counter-claims of the potential for ecological and environmental damage on their websites. The challenge on the environmental front can best be illustrated by the findings in a recent paper by Rabone et al. (2023) that notes that 5,142 unnamed metazoan fauna species have been identified in the CCZ.

Deep-sea mining may also impact other business sectors too; Amon et al. (2023), for instance, highlight that deep-sea mining in the CCZ could have repercussions for the tuna fishing industry in the area, which is worth around US$5.5blnpa. Even more staggering numbers have been presented by Planet Tracker (2024). The NGO estimates that at least US$500bln of corporate value and natural capital would be destroyed if polymetallic nodules are mined in international waters. They estimate a figure of US$30-132bln – 3 to 13 times the combined GDP of all Pacific island small states – as a result of negative returns on invested capital from mining deep-sea nodules and due to the resulting increases in the cost-of-capital for high-cost terrestrial nickel, cobalt and copper mines. The NGO also estimates that at least a further US$465bln of value destruction would result from habitat destruction of the deep-sea's ecosystem. It argues that from a natural capital perspective, preserving the planet's abyssal plains is at the very least worth ten times more than exploiting them. The NGO adds its support to calls for a moratorium on deep-sea mining.

Managing deep-sea mining and environmental challenges

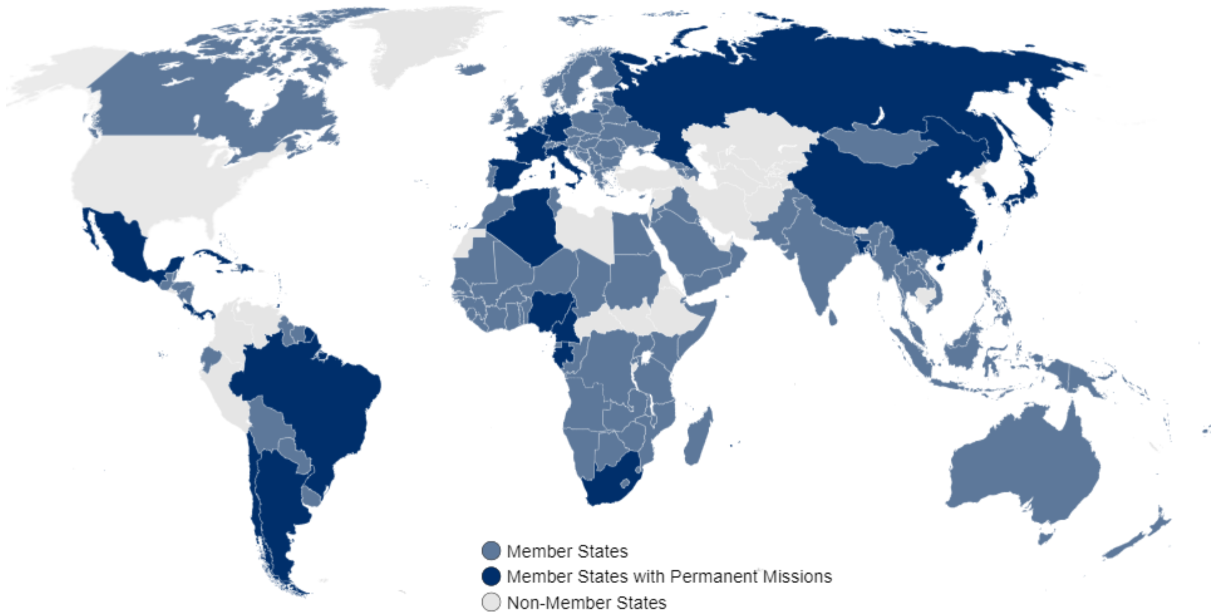
Economic interest in manganese nodules began in the late 1950s, with a number of consortia formed to consider exploiting them in the mid-1970s with a view to commencing mining in the late 1970s/early 1980s, according to Hein (2016). Initial plans were scuppered by a number of factors including weak commodity prices, challenges in developing economically viable technology, environmental concerns and issues over ownership and territorial rights. One of the first attempts to commercialise deep-sea mining was Nautilus Minerals, founded in 1997 but declared bankrupt in 2019, with its copper, gold and silver-rich Solwara-1 project in the territorial waters of Papua New Guinea. The company was subsequently taken over by Deep Sea Mining Finance.

The deep-sea covers around 54% of the total area of the world's oceans and mineral resource extraction is controlled by the International Seabed Authority (ISA), set up in 1994 under the auspices of the United Nations Convention on the Law of the Sea. The ISA (2024a) notes that it currently has 168 member states, plus the European Union, but not the USA (Figure 11). To date, the ISA has only issued contracts for research purposes, but was due to have established a regulatory framework for commercial mining before a 9 July 2023 deadline, or accept mining applications under whatever mining regulations exist.

One of the key challenges (and ironies, perhaps) in securing and interrogating biodiversity data and researching the potential environmental and ecological impact is that the very companies that seek exploitation licences are also those that have contributed huge amounts of data. The Metals Company (2023) claims that at its CCZ NORI project, in the waters of Nauru, it has contributed nearly 60% of all the biodiversity data of all ISA contractors to ISA's DeepData platform, which has been published to the OBIS-ISA node (Ocean Biodiversity Information System). This percentage may well now be higher following the submission of the largest environmental dataset yet to the ISA, announced in May 2024 (The Metals Company 2024c).

One of the most recently announced scientific studies (Sweetman et al. 2024), undertaken on The Metal Company's NORI-D licence area in the CCZ suggests evidence of 'dark oxygen'. The study hypothesises that seawater electrolysis on the surface of polymetallic nodules on the abyssal seafloor of the CCZ, some 5km deep, produces oxygen without the 'normal' action of photosynthesis that would require sunlight. The discovery of 'dark oxygen' could potentially support life on the sea floor, and is likely to add to calls for a moratorium on deep-sea mining pending further research.

Figure 11- Member states of the International Seabed Authority



Source: International Seabed Authority 2024

A growing number of countries have called for a moratorium, pause or ban on deep-sea mining (Guardian 2023) and governments, like the UK, for instance, are forming research networks to review the environmental impact of deep-sea mining (UK government 2024). At the end of the July 2023 ISA two-week session, and having failed to develop regulations for exploitation, the ISA agreed to finalise the rules for exploitation by July 2025. While technically, companies may now be able to apply for mining licences, the delay and the growing number of countries against near-term mining, together with businesses that have vowed not to use raw materials from deep-sea mining (including BMW, Volvo, Samsung and Google), as noted in the Mining Journal (2023c), suggests that near-term deep-sea mining may not materialise.

As ever though, that stance is not universal and in January 2024 lawmakers in Norway voted to allow deep-sea mineral exploration in the Arctic Ocean over an area of around 280,000km2 (greater than the size of the United Kingdom), putting Norway at odds with its neighbours, the EU and UK. According to a

Norwegian government white paper published in June 2023, Norwegian continental shelf sulphide crusts may contain as much as 45mln t of zinc, while manganese crusts which are also present may contain around 3mln t of cobalt (mining.com 2024a).

Of at least equal significance, is the signing into law by President Biden (The Metals Company 2024a) of the National Defense Authorization Act (FY24) which directs the Assistant Secretary of Defense for Industrial Base Policy to submit a report to the House (of Representatives) Armed Services Committee assessing the processing of seabed resources of polymetallic nodules domestically covering current resources and controlling parties, current domestic (US) capability for deep-sea mining and material processing, and a roadmap recommending how the USA can source and process these materials (House of Representatives 2023). In March 2024 Members of the House of Representatives also put forward a bill entitled the Responsible Use of Seafloor Resources Act which seeks to 'support international governance of seafloor resource exploration and responsible polymetallic nodule collection by allied partners' and to 'provide financial, diplomatic, or other forms of support for seafloor nodule collection, processing and refining' (The Metals Company 2024b). This was followed up in May 2024 by a call, in the House version of the fiscal 2025 National Defense Authorization Act, for US$2mln to be allocated to the Defense Department's Industrial Base Policy Office to study the feasibility of developing domestic capacity to refine polymetallic nodules while The Metals Company's US subsidiary has applied for a US$9mln grant under the Pentagon's Defense Procurement Act Title III for feasibility work on a domestic refinery for nodule-derived intermediate products (The Metals Company 2024d).

Japan is also looking at trial exploitation. A recent report (The Japan Times 2024) notes the discovery of 234mln t of nodules in a 100 sq.km. survey area near Minamitorishima island, with sufficient nickel and cobalt to supply 75 and 11 years respectively of Japanese demand. 2,500tpd of the mineral resource are expected to be extracted in an experimental project commencing by end-March 2026. China has also entered the race to explore deep-sea mining; one of its deep-sea vehicles recently broke several national records, including a record-breaking dive to over 4,100m (mining.com 2024i, china.org.cn 2024). Pressure continues to mount on the International Seabed Authority, as seen at the twenty-ninth session of the International Seabed Authority Council and Assembly in July/August 2024, where the latest draft of the possible rules for seabed mining were discussed amidst continuing support by groups like the International Union for Conservation of Nature (2024) for a moratorium on deep-sea exploitation as environmental research continues to lead to the discovery of new species. The recent election of Ms. Leticia Carvalho as the new Secretary-General may slow down the push for commercial development; she is thought to be more environmentally and less commercially minded than her predecessor, Michael Lodge (ISA 2024b, mining.com 2024j).

The financial impact of allowing or disallowing deep-sea mining therefore carries huge economic and ecological consequences, and until more clarity on these issues is available, a moratorium would seem to be a sensible near-term solution.

Mining in space

Once purely in the realms of science fiction novels and movies, there is growing interest in mining in space. Some of the most recent comments come from NASA and involves mining on the Moon as part of the Artemis mission (mining.com 2023c). The aim is to start excavation and pilot processing in 2032. This, and other elements of the Artemis mission, could ultimately aid in the development of manned missions to Mars. Privately-owned companies like Moon Express and ispace also hope to explore for and develop resources on the moon (Company websites (1) 2024). There has also been interest in the concept of asteroid mining for several decades, but we are still a very long way from economic reality. A number of companies built around the desire to mine asteroids have come and gone, such as Planetary Resources and Deep Space Industries, according to Wikipedia (1) (2024), with others, like Asteroid Mining Corp. and AstroForge are now taking up the running (company websites (1) 2024). However, we are still several decades away from economically viable space mining. Any commercial activity would likely need to fall under the auspices of the Outer Space Treaty, which is backed by all major spacefaring nations. Given the difficulties on agreeing if or how to exploit deep-sea mining, space mining is likely to prove to be at least as contentious an issue.

A costly venture

The impediments to mining in space are immense, as illustrated by Moore et al. (2022). In the first instance, mineral extraction is likely to focus on bringing raw materials back to Planet Earth. But think of how much easier and cheaper it is to explore, mine and process on Earth (with documented geology and exploration/mining history, and exploration/mining/processing techniques that are known to work, for instance) than in space, where there is such a limited knowledge base. Huge transportation costs will likely mean that processing will need to take place in space, and exorbitant exploration, mining and processing costs will mean that only uniquely high-grade deposits and high-value commodities will be transported in treasured payloads back to Earth. If there is a 1 in 10,000 chance that an identified mineral prospect on Earth will be developed into a new mine, and that the average terrestrial discovery cost is US$240M, just imagine what it is likely to be in space – certainly many multiples of these figures.

Urban mining and the circular economy

The German Environment Agency defines urban mining as the 'integral management of the anthropogenic stock with the aim of obtaining secondary raw materials from durable products, buildings, infrastructures and deposits' (Müller et al. 2019). The concept looks to the long-term management of all anthropogenic stock (i.e. material originating from human activity) and therefore includes waste management and recycling of long-life materials and plans for capturing and re-using yet-to-be-generated redundant materials through better planning and design of newly and to-be-constructed goods.

Urban mining, in the sense of the use of the term for critical materials, is likely to relate to multi-commodity recovery from generally small and typically electronics-related components. It can be difficult to isolate the individual elements from these components, each of which may contain only very small amounts of a multitude of metals and minerals and therefore we need to see further technological advances in recovery and progress in increasing recovery rates, as well as the political willpower from governments to provide assistance.

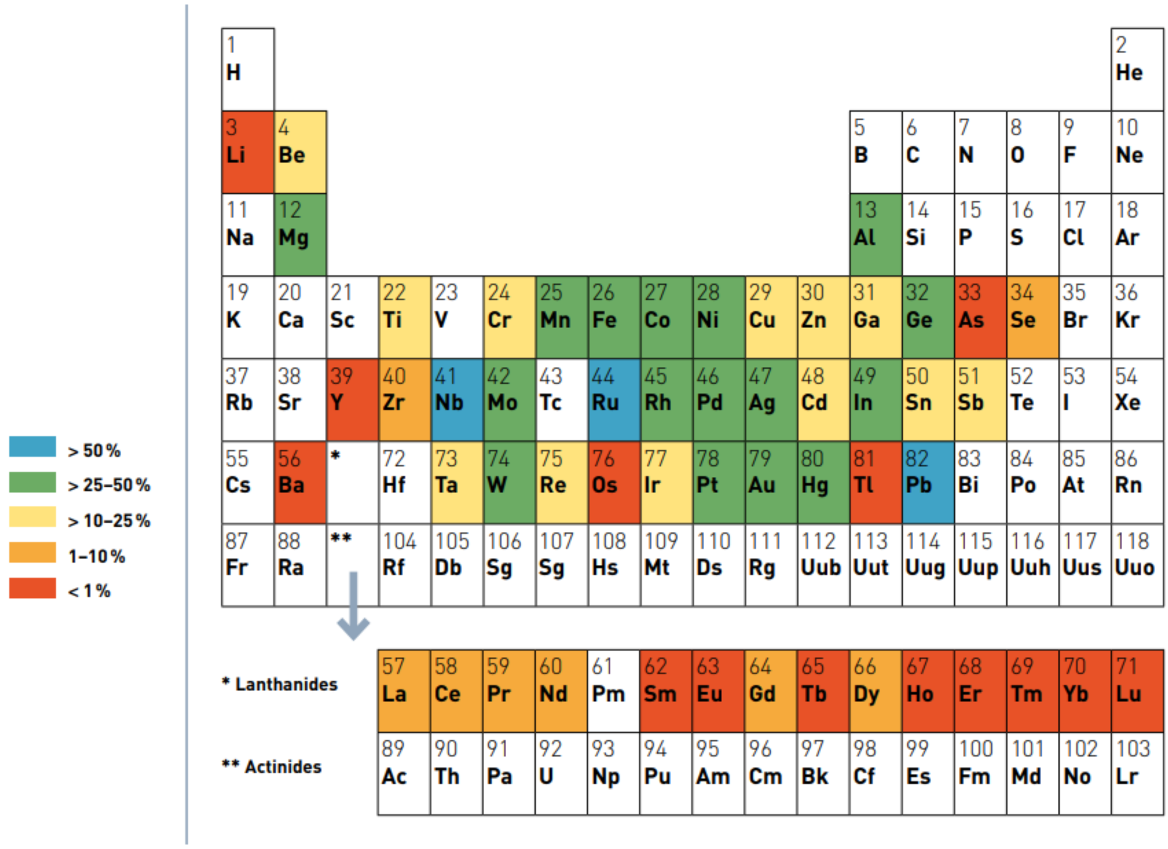
Urban mining has one significant, and key, limitation. Production of raw materials for re-use in urban mining is unlikely to ever match current and future raw material demand (Espinoza et al. 2020). Clearly the greatest source for the re-use of materials are our largest population centres, and while a recycling plant may not carry quite the stigma of conventional mining, not everyone wants to live next door to a recycling facility either. There are advantages of urban mining though, such as reduced transportation distances (relative to newly-mined materials), reductions in landfill tonnage and a reduced energy footprint (for instance, the recycling of a metal typically uses substantially less energy than producing the metal in the first place).

Subtle re-balancing of supply

As urban mining grows, there will also be a subtle rebalancing of raw material supply, from mining locations often in far-flung corners of the world, to industrial nations that are already the key manufacturing hubs. The trend will be slow, however. A Li-ion battery is likely to have a lifespan of 10-15 years, and recycling is expected to yield anywhere between zero and 80% of the lithium contained in end-of-life batteries, equating to around 6% of total lithium supply in 2030, according to McKinsey (2022). But as Figure 12 illustrates, recycling rates for CRMs are low according to Graedel et al (2011).

Li-ion battery recycling has attracted a wide array of corporates such as Veolia, the French-based multinational with a number of battery recycling plants across the world (but better known for its water, waste and energy management), to Aurubis, based in Germany and with a focus on copper smelting, refining and products over its greater than 150-year history, and finally to juniors like Lithium Australia which is developing a hydrometallurgical technique for recovering all metals, including lithium, from Li-ion batteries (company websites (2) 2024).

Figure 12 - Recycling rates for CRMs are low



Source: Graedel et al. 2011

Better design would enhance recoveries

As noted by Harper et al. (2023), there are a vast array of Li-ion battery materials' recovery techniques in use or under development including pyrometallurgy, hydrometallurgy, short-loop (the recovery of intermediate products that can be reused), direct recycling and biological recovery. Battery design tends to focus on first-use – cost and material content, efficiency and mileage achievability - but more thought needs to go into the recyclability of Li-ion batteries when they reach end-of-life (Harper et al. 2023, Thompson et al. 2020). This challenge is compounded by the general lack of codes, standards and regulations for the treatment of recycling and the creation of second-life products (Lambert et al. 2023). Gaines and Dai (2023) outline a further, critical, challenge. Battery chemistries are continually evolving, and since batteries are a long life product, end-of-life battery streams are likely to contain multiple cathode technologies, so cathode materials from some cells may be obsolete by the time they are available for recycling. The challenge then will be to separate black mass material (shredded battery pack material) to economically recover the broadest array of cathode components.

Vertical integration in some CRMs markets

In other, smaller, CRMs markets, such as Rare Earth Elements (REEs), there is a greater approach to vertical integration. If one considers Mkango Resources, for instance, the company hopes to develop the Songwe Hills mine in Malawi, build the Pulawy RE separation plant in Poland, and through its Maginito subsidiary, pursue downstream REEs technologies in the UK and USA through the recycling of NdFeB magnets (from EV motors) and the development of innovative REE alloy, magnet and separation technologies (company websites (2) 2024).

Table 3 – Critical raw material national agreements January 2020-May 2024

Agreement	Countries	Start
Joint action plan on critical minerals collaboration	Canada, USA	Jan-20
Critical minerals mapping initiative	Australia, Canada, USA	Oct-20
Critical minerals working group	Brazil, USA	Nov-20
Strategic partnership on raw materials	Canada, EU	Jun-21
MOU to form strategic partnership on critical raw materials	EU, Ukraine	Jul-21
Strategic dialogue on critical minerals	Australia, France	Aug-21
Comprehensive strategic partnership	Australia, S. Korea	Dec-21
Collaboration to strengthen supply chain for battery technologies	EU, USA	Mar-22
Minerals Security Partnership (MSP)	Australia, Canada, Estonia, EU, Finland, France, Germany, India, Italy, Japan, Norway, S. Korea, Sweden, UK, USA	Jun-22
Net-zero technology acceleration partnership	Australia, USA	Jul-22
Critical minerals investment partnership	Australia, India	Jul-22
Critical Minerals Partnership	Australia, Japan	Oct-22
MOU to form strategic partnership on critical raw materials	EU, Namibia	Nov-22
MOU to form strategic partnership on critical raw materials	EU, Kazakhstan	Nov-22
Sustainable Critical Minerals Alliance	Australia, Canada, France, Germany, Japan, UK, USA	Dec-22
Agreement on strengthening critical minerals supply chains	Japan, USA	Mar-23
Joint statement of intent on collaboration on critical minerals	Canada, UK	Mar-23
MOU to support Korean critical minerals and battery manufacturing investments in North America	S. Korea, USA	Apr-23
Joint statement of intent on collaboration on critical minerals	Australia, UK	Apr-23
Joint declaration of intent on a critical minerals value chain feasibility study	Australia, Germany	Apr-23
MOU on cooperation in critical mineral supply chains	Canada, S. Korea	May-23
Quad Statement of Principles on Clean Energy Supply Chains in the Indo-Pacific	Australia, India, Japan, USA	May-23
Climate Critical Minerals and Clean Energy Transformation Compact	Australia, USA	May-23
Joint communique on critical raw materials	France, Germany, Italy	Jun-23
MOU to form strategic partnership on critical raw materials value chains	Argentina, EU	Jun-23
MOU to form strategic partnership on critical raw materials value chains	Chile, EU	Jul-23
MOU to secure critical minerals	Japan, Zambia	Aug-23
Scope of work to secure critical minerals	Japan, Namibia	Aug-23
Scope of work to secure critical minerals	DR Congo, Japan	Aug-23
Trilateral economic security dialogue	Japan, S. Korea, USA	Aug-23
Sectoral working group on critical minerals	Canada, Japan	Sep-23
MOU to form strategic partnership on critical raw materials value chains	EU, Zambia	Oct-23
MOU to form strategic partnership on critical raw materials value chains	DR Congo, EU	Oct-23
Indo-Pacific Economic Framework (IPEF) Critical Minerals Dialogue	Australia, Brunei, Fiji, India, Indonesia, Japan, Malaysia, New Zealand, Philippines, Singapore, S. Korea, Thailand, USA, Vietnam	Nov-23
MOU establishing an EV collaboration mechanism	Australia, Indonesia	Nov-23
LiMongolia pilot project	France, Mongolia	Jan-24
MOU on sustainable raw material chains	EU, Rwanda	Feb-24
Joint statement on critical minerals cooperation	Australia, Canada	Mar-24
Partnership on sustainable critical & strategic minerals	Australia, EU	May-24

Source: Mining Journal 2024h (Aspermont research using official announcements), European Commission 2024b

Political challenges

We have already noted the long lead time to develop a mine; typically anywhere from 12-29 years from discovery to start-up. In addition, of course, is the time from exploration initiation to discovery. If we hope to satisfy the growing need for critical raw materials, mining companies need to see a reduction in political impediments to rapid development, and an easier route to fundraising. Many of the key points that we focus on in this report were succinctly outlined in a keynote presentation at the Prospectors and Developers Association of Canada (PDAC) 2024 convention by Michael Stanley, mining lead at the World Bank. Stanley notes that the World Bank forecasts a global population of 10 billion by 2050, and outlines the surge in commodity demand amongst a need to focus on poverty reduction, 'unprecedented urbanisation', the energy transition and the need to reduce mine discovery-to-production lead times (Mining Journal 2024d).

Minerals security partnerships

At the national level of politics, and in particular in the major developed nations, there is a growing political understanding of the need to secure additional raw materials. In 2022, at the PDAC convention, the world's largest mining event, the creation of the Minerals Security Partnership (MSP) was announced. MSP is a partnership of leading economies and includes Australia, Canada, Finland, France, Germany, Japan, South Korea, Sweden, UK, USA and the European Union and is 'committed to build robust, responsible critical mineral supply chains to support economic prosperity and climate objectives' (US Dept. of State 2022). Other multi-country initiatives include the Indo-Pacific Economic Framework (IPEF) Critical Minerals Dialogue announced in November 2023 (Mining Journal 2024h).

There are also numerous bilateral agreements, typically country-to-country, but also region-to-country. Examples, as noted by Reuters (2023d) and Willems et al. (2023), include agreements between the EU and Canada, Kazakhstan, Namibia and the Ukraine, and between South Korea and Western Australia, all of which have been signed in recent years. Indeed, a total of 39 national collaboration agreements have been made between January 2020 and May 2024 – essentially one a month on average, as illustrated in Table 3, with, typically, a number of multi-month announcements over the last 18 months or so. At the heart of all of these agreements is a desire to reduce the actual and perceived influence that China currently has on supply chains. The US has augmented a series of mineral security agreements with trade tariffs against China, announcing in May 2024 (White House 2024) an increase in tariffs on US$18bln of imports including, amongst others, critical minerals.

COP out

These agreements, however, are generally light on action – the detail on how to finance and propel the development of CRMs for climate change. If you look at the proceedings of the COP26 (Glasgow) and COP27 (Egypt) global climate change conferences you will be hard pushed to find any reference at all as to how to fast-track the development of CRMs production to achieve the laudable desire to promote alternative energy sources and reduce the use of fossil fuels. News from the most recent conference, COP28, held in Dubai in December 2023, claims that the conference agreement signals the 'beginning' of the end of the fossil fuel era, but again there is no reference to how alternative energy sources will be championed, and no mention of the critical raw materials needed to achieve Net Zero (UN Climate Change News 2023). If governments want a to switch to electric cars, they need to be aware, as the IEA (2021b) notes, that an electric car uses over six times the 'green' metals and minerals of a conventional petrol/diesel vehicle.

Policy misalignment

On paper, these partnership agreements between countries look to be the way forward. However, there is one aspect that is frequently overlooked, and that is the misalignment between national resource policies and Net Zero targets. As Owen et al. (2023) point out, the misalignment between countries with regards to national resource inventories and policy actions 'could lead to global-scale delays in mitigating climate change and an uneven energy transition structured around national resource endowment, wealth and inequality'. The paper notes greater alignment of mineral extraction policies and energy transition minerals' demand is more strongly aligned in OECD countries (36 of the Western World's leading economies) than non-OECD counterparts. Greater policy alignment and cooperation between (primarily) natural resource-deficient OECD countries and (generally) more natural resource-rich non-OECD countries could result in a win-win outcome; the provision of raw materials for the leading western industrial nations, and job and wealth creation, and regional development, of non-OECD resource-rich countries.

National political impediments to mine financing and development

When commodity prices are high and mining companies are reporting record revenues and profitability, not to mention paying increasing dividends to shareholders, it is tempting for governments at all levels (national, regional and local) to wish to increase taxation or royalty rates to claw back more of the financial benefit of mining, particularly in regions where populist politics is to the fore. This ignores, however, the many years of time and money spent by a mining company in exploration, and the risks involved in project development. Governments need to remember that while geology has a lot to do with where a mining dollar is spent, at least as important is the risk and cost of doing business in a particular jurisdiction. As illustrated in Table 4, in the Mining Journal Intelligence survey of mining investment risk, the provinces and states of Canada, Australia and the USA tend to rank particularly well, along with Nordic countries (Mining Journal Intelligence 2021 & 2023). Canada's Fraser Institute produces a similar survey which also shows Canada, Australia and the USA as the preferred jurisdictions, though the least attractive countries tend to differ based on the experience of corporate participants in each survey (Mining Journal Intelligence 2021 & 2023, Fraser Institute 2024). It is not just the relative regional ranking that can dictate where a mining dollar is spent, but also the trend.

Table 4 - Mining Investment Risk - Top and Bottom jurisdictions (out of 110 regions/countries)

Top 10			**Bottom 10**
1	Newfoundland	1	Nigeria
2	New Brunswick	2	Burundi
3	Manitoba	3	Uganda
4	Saskatchewan	4	Ethiopia
5	Greenland	5	Philippines
6	NW Territories	6	South Korea
7	Finland	7	India
8	Western Australia	8	Thailand
9	South Australia	9	Jamaica
10	Northern Territory	10	Myanmar

Source: Mining Journal Intelligence 2023, 2022 Mining Investment Risk survey

Chile – increasing taxation reduces attractiveness

For instance, in the Mining Journal Intelligence 2021 World Risk Report, Chile, the world's largest copper miner, scored 75 points and ranked tenth out of 106 countries/regions. In the 2022 survey, however, the country scored 66 points and had fallen to 50th out of 110 countries/regions. In other words, many more parts of the world were deemed to be more attractive destinations than Chile for a mining investment dollar in 2022 than was the case in 2021. Populist president Gabriel Boric, who amassed more votes than any previous president, came to office in March 2022 with the promise of increasing taxation on the mining industry. In May 2023, Chilean politicians approved an amended mining royalty and tax regime which will see the maximum tax and royalty take rise to 46.5% compared with the current take of between 41-44%, higher than is typical in other key copper mining countries. The scheme is expected to add around US$1.5bln to the Chilean state, of which c.US$450mln will be destined for social spending by regional governments (mining.com 2023b, KPMG 2023).

Chile has also announced a strategy to create public-private partnerships in the lithium industry. Initially thoughts were that this amounted to nationalisation (Reuters 2023b). However, it now appears that a more collaborative approach is envisaged (mining.com 2023a). This is clarified in the May 2024 announcement from Codelco (2024) of a partnership agreement between the Chilean state-owned copper giant, Codelco, and SQM to operate and develop the Salar de Atacama between 2025 and 2060. Between 2025-2030 the Chilean state with receive 70%, and from 2031, 85%, of the operating margin of the new production through payments to Corfo (the country's economic development agency), taxes and the profits received by Codelco as a shareholder (Codelco will own 50% plus one share in the partnership). Further indications of the strategy were made apparent in December 2023 when Lithium Power International (LPI) announced that it was to be acquired by Codelco for around A$385M, giving Codelco control of LPI's Chilean Maricunga salar project (Lithium Power International 2023). As part of the new lithium initiative, Chile invited companies to express an interest in a Special Lithium Operation Contract. At the close of the initiative in mid-June 2024 88 proposals had been received from over 50 companies from 10 countries. More clarity about the contracts is expected in April/May 2025 (Mining Journal 2024m).

Mali – increasing local gold mining ownership

The problem for mineral-endowed nations is that when commodity prices are low, and exploration is scarce, government's cut taxes, royalties and local ownership requirements to try to incentivise exploration and project development. When commodity prices are strong, governments try to claw back a greater return from a project. One of the latest such moves is in Mali where the government is seeking to take a 30% stake in mines (compared to up to 20% previously), with a further 5% for local private interests, according to Reuters (2023e). The plans are primarily aimed at the gold mining industry (Mali's gold exports were worth US$3.24bln in 2022 (Reuters 2023a)), but the country also has two advanced lithium projects, including Goulamina (Ganfeng, previously Leo Lithium) where construction is underway, and Bougouni (Kodal Minerals) which is expected to be in production in 2024 (company websites (3) 2024). In May 2024, Leo announced the sale of its stake in Goulamina to the Chinese lithium producer Ganfeng, and the migration of the project to the 2023 Malian Mining Code, lifting potential Malian government interest from 20% to 30%, plus 5% for local interests (Leo Lithium 2024).

Panama – forced closure of the only significant mine in the country

There are more recent, and more dramatic, developments in Panama. The only mine of any significance in the country is the Cobre Panama copper mine, operated by Minera Panamá S.A. (MPSA), a subsidiary of Canadian miner First Quantum Minerals (2023). A Concession Agreement was signed between MPSA and the Panamanian government in 1996, leading to the investment of US$10bln in the mine and related infrastructure. Commercial production began in 2019. Following a Supreme Court decision in 2017, and at the request of Panama's government, MPSA renegotiated the terms of the Concession Agreement, a process which included public consultation and regulatory signoff. This was approved by Contract Law 406 by the National Assembly on 20 October 2023. However, on 28 November 2023, the plenary of the Supreme Court of Justice declared Law 406 unconstitutional, and the government of Panama has ordered mine closure, which may impact up to 7,000 jobs (Panama Wire 2023). Having spent US$10bln on the project, this is clearly not good news for First Quantum, nor for the Panamanian economy and workforce. It also vividly illustrates the impact of populist politics on the world's ability to achieve Net Zero. The latest developments are that First Quantum is seeking more than US$20bln in compensation before the International Court of Arbitration (ICC) in Miami and US$30bln before the World Bank's International Centre for Settlement of Investment Disputes (ICSID) in Washington DC. Additionally, Franco-Nevada (which has a precious metals stream on the project) is seeking US$5bln before the ICSID and Korea Mine Rehabilitation (10% project owner) is seeking US$747.1mln before the ICC in another arbitration claim. Further, a number of suppliers and contractors are seeking US$900mln before the ICSID and ICC, including Liebherr which is claiming under the French FTA agreement (Mining Journal 2024i & 2024l). President-elect Mulino (a strong supporter of the outgoing president, Martinelli) has said he will not engage in talks with First Quantum while arbitration proceedings are underway.

Mexico – banning open-pit mining and nationalising lithium

Meanwhile, in Mexico the country's President Obrador has called for a ban on open-pit mining on environmental grounds, though some argue this is a politically-motivated move against the country's largest miner, Grupo Mexico. The President lacks the supermajority needed to push through the required constitutional amendments, but his likely successor in the June presidential election, Claudia Sheinbaum (from the same political party) says she will adopt his proposals (mining.com 2024c & d, Mining Journal 2024b). Again, a far-ranging proposal such as this will have a detrimental impact on mining investment and job creation in the country.

This development follows the Mexican government's decision to nationalise the embyonic Mexican lithium industry. Ganfeng Lithium, which is hoping to develop the Sonora project, has taken the Mexican government to arbitration at the World Bank's International Centre for Settlement of Investment Disputes over the cancellation of its concessions. The Mexican government is seeking an agreement with the Chinese company (mining.com 2024g).

Good news – at the national level…

While most newsflow tends to highlight negative government intervention, there is on occasion evidence of governments helping to incentivise the mining industry. For instance, at the national level, Canada is looking at how it can expedite the permitting process for new CRM mines from 12-15 years to 5 years (Mining Magazine 2024). Another good example is Australia where, in February 2024, and as a result of very weak nickel prices and the threat of widespread mine closures, the government added nickel to its Critical Minerals List. This will allow nickel companies to access low interest loans and grants from the country's A$4bln Critical Minerals Facility and, in addition, the Western Australian government is offering nickel miners royalty relief (mining.com 2024 e & f).

…and at the corporate level

And then at the corporate level, in Indonesia for instance, PYX Resources (2023) has been exporting zircon under rules applicable for non-metal commodities. The government has now approved the export of titanium dioxide feedstock (ilmenite and rutile) on the same basis, which should allow PYX to increase export volumes and revenues.

Another example is the October 2023 announcement from Agnico Eagle Mines (2023) that the Supreme Administrative Court of Finland had upheld the company's right to operate the Kittila gold mine at 2mln tpa, overturning a 2022 appeal in the Vaasa Administrative Court that determined that the Regional State Administrative Agency of Northern Finland should reconsider its granting of environmental and water permits in 2020.

Regional political input

Mining companies also need to contend with regional, provincial and local governments. In some countries, like the USA, Canada, Australia and Argentina, the local provinces or states have a significant say in the legislation impacting exploration, development and mining. Frequently, but not always, this tends to add impediments to rapid project progression. But again, this is not always the case.

Salta, Montana, Michigan and Ontario – examples of positive regional initiatives

In Argentina's Salta province, mining.com (2023d) notes that the legislature has discussed ways to expedite the processes relating to mining environmental and social impact assessments. At present, these assessments are first submitted to the provincial Mining Court, and from there, are forwarded to the Mining and Energy Secretariat. A plan is under consideration to remove the first step in this process to improve the efficiency and monitoring of these procedures by ensuring that initial submissions and renewals of the assessments are managed in one place. Salta is one of Argentina's key lithium-rich salar provinces, playing host to six advanced projects with operational processing plants and 4 other early development projects.

A second example was the announcement by Sandfire Resources (2024) stating that in February 2024 the Montana Supreme Court ruled to reverse a 2021 district court decision, thus instructing the District Judge to have the Montana Department of Environmental Quality completely reinstate the Mine Operating Permit for Sandfire's Black Butte copper project.

In March 2024, Highland Copper announced that the Michigan Strategic Fund Board had awarded a US$50M performance-based grant from the Strategic Site Readiness Program for infrastructure development pertaining to the in-state Copperwood copper project.

More recently, in May 2024, the Ontario government (Ontario 2024) announced that it would provide an additional C$15mln over three years to expand its Critical Minerals Innovation Fund, which started in November 2022 and provides grants in Ontario for local critical minerals supply chain projects.

These are all steps in the right direction. More initiatives like this, aimed at reducing the timeframe from discovery to production and across a broader geographical spectrum, would be welcomed, however.

Defining key ESG issues

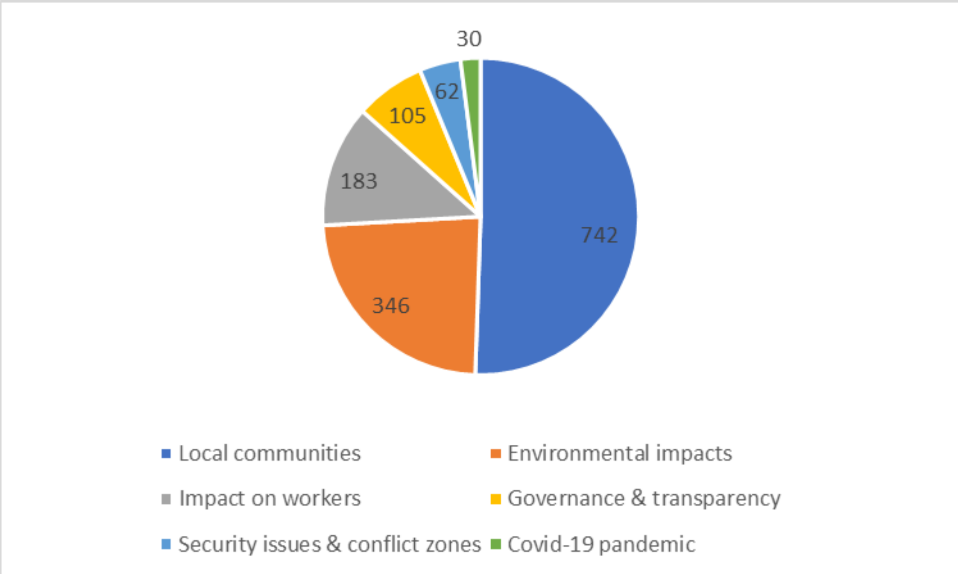
Mining companies are now expected to publish, and follow, their environmental, social and governance (ESG) framework and principles. Deloitte (2024) offers the following definition: 'The goal of ESG is to capture all the non-financial risks and opportunities inherent to a company's day to day activities'. The larger the company the greater the ESG footprint, but even juniors need to increasingly adhere and comply with ESG principles. For instance, in the UK, many juniors (even pure exploration companies) adhere to the 10 principles of the Quoted Companies Alliance Corporate Governance Code (2023) which covers overall governance principles, including social, but does not specifically highlight environmental issues. Inevitably, formulating ESG policies and maintaining them will add to the cost of business and have an impact on mining operating costs, though this is hard to quantify.

Substantial work on ESG for the majors

For larger companies, there are significantly higher levels of reporting on ESG issues. Rio Tinto (2024d), for instance, publishes four reports annually; a Climate Change Report, a Sustainability Fact Book and a Communities and Social Performance Commitments Disclosure outlining its actions and performance in these areas, as well as a Tax and Royalties Paid Report (the company paid out a total of US$10.8bln in 2022, followed by US$8.5bln in 2023, and US$76.0bln in total over the last 10 years). All of these actions are laudable, but companies need to ensure that all employees are fully aware and accept the principles that their employer has committed to. After all, it was only four years ago that Rio Tinto blasted 46,000 year-old Aboriginal rock shelters at Juukan Gorge to expand its Pilbara iron ore operations (Guardian 2020).

Mining companies, and their customers, are keen to demonstrate how 'clean' the raw materials are that they produce and consume. For instance, Circulor is a company that provides third-party audits on material traceability. It recently confirmed end-to-end traceability for SQM's Salar de Atacama lithium supply to Volvo Cars (Circulor 2023). The Initiative for Responsible Mining Assurance (IRMA 75) certificate was achieved after auditing 26 functions, including water management, human rights, greenhouse gas emission and fair labour practices, amongst others. In total, 40 critical requirements must be met and 75% of the requirements in each of the four Principle areas of the Standard (Initiative for Responsible Mining Assurance 2024).

Figure 13 - 1,468 ESG allegations by category made against the mining industry 2010-2022



Source: Business & Human Rights Resource Centre 2023

Engaging with local stakeholders

It may be stating the obvious, but for any exploration programme, project development or mining operation, it is imperative that the local community – residents and politicians – understand your project, understand the benefits and understand all the mitigation that you have put or plan to put in place to prevent disruption and environmental concerns. This is your licence to operate. The Business & Human Rights Resource Centre (2023) has published a thorough review which illustrates the scale of the challenge in relation to indigenous peoples, water usage, corruption, labour rights and more, illustrated in Figure 13. A 2024 update from the NGO notes that of 60 legal cases launched (to 31 May 2024) globally by Indigenous Peoples, other communities and workers directly impacted by human rights harms from the growth of the renewable energy value chain, two-thirds (40) are accounted for by mining for transition minerals, with the balance from hydropower and dam projects (9), wind energy (9) and solar energy (2) (Business & Human Rights Resource Centre 2024).

Las Bambas – a vivid illustration of what can go wrong

The Las Bambas copper mine in Peru, operated by MMG (a Hong Kong Stock Exchange-listed subsidiary of China Minmetals), was reported to have had the highest number of allegations against it both in 2022 and overall. Since the mine started operation in 2016, it has suffered over 600 days of blockades and other disruption, according to Bloomberg (2023). The key issues relate to dust and noise pollution (copper concentrate is trucked from the mine through a number of communities) and demands for jobs, amidst additional demands for compensation. An estimate by Espinosa (2022) suggests that the mine loses around US$9.5mln each day it is blockaded, so to date approximately US$6bln may have been lost. Once trust with the local community is lost, it is hard to recover. The clear message is that mining companies must engage early, and honestly, with local stakeholders and endeavour to take their concerns into account, particularly when changing plans. This can be a particular challenge for junior mining companies, who may lack the financial buffer and skillset, especially when there is no guarantee of exploration success. For the record, Xstrata, the previous pre-production owner of Las Bambas, had planned to transport copper concentrate via a 206km pipeline rather than by road (Espinosa 2022).

Traditional landowner engagement

A key aspect is the need to engage with indigenous traditional landowners and residents, sometimes referred to as First Nations, where there may be significant cultural issues, and it is vital that their values, traditions and concerns for the land are fully addressed with regards to the impact of mining. One example, following the Juukan Gorge incident referred to before, is the engagement of Rio Tinto (2020) with the Puutu Kunti Kurrama and Pinikura people. Another, is the more recent incident, also in Australia, involving Sandfire Resources and the disturbance of artifact scatter of the Yugunga-Nya (Sandfire Resources 2023).

Engagement is vital, indeed necessary, in Canada as well as in Australia. Exploration targets and mines are often located on or near to the traditional lands of First Nations people, and as well as addressing their concerns, there are also opportunities for the mining company to offer training and jobs to these people. Relationship agreements (impact benefit agreements or collaboration agreements) between mining companies and Indigenous communities are widespread in Canada; there are currently over 500 agreements in place (Mining Association of Canada 2024, Natural Resources Canada 2024). Sometimes, however, agreement cannot be reached. In October 2023 the Nunavut Impact Review Board (2023) recommended against allowing Agnico Eagle Mines to extend the mine life at its Meliadine gold mine by 11 years to 2043.

However, indigenous groups are not always against mine development. Northern Dynasty Minerals (2024), for instance, reports that two Native Village Corporations nearest to its Pebble Cu-Mo-Au-Ag project in Alaska have filed suit against the Environmental Protection Agency claiming that the agency has exceeded its authority in vetoing the project, thereby preventing the creation of jobs, economic activity and revenue that would benefit the communities.

There are also examples of cooperation such as the agreement between the Taku River Tlingit First Nation, the government of British Columbia and Teck to jointly advance environmental remediation at the polluting Tulsequah Chief mine site. Teck will voluntarily undertake and fund site investigation in 2024-25 in a move towards a final Tulsequah Reclamation and Closure Plan. A predecessor company of Teck operated the underground copper, zinc and lead mine between 1951 and 1957. The current owner, Chieftain Metals, went into receivership in 2016.

'Greening' in the mining industry

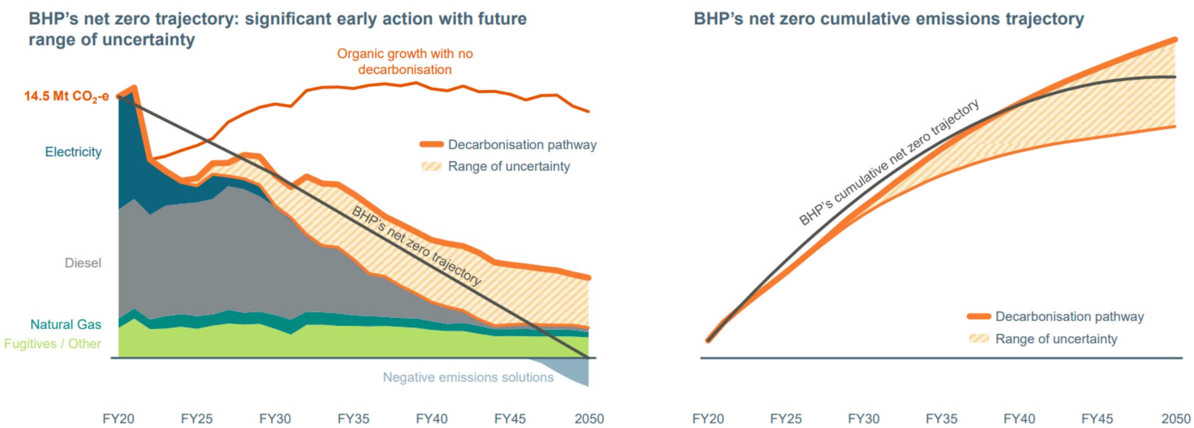
Like every other industry, the mining industry is looking at how it can improve its environmental credentials. Inevitably, mining has a poor reputation and must do more to promote what it is doing to improve its environmental footprint. By definition an open-pit mine leaves a visible scar on the landscape (unless it is later infilled and 'regreened'). Disasters like the failure of the Brumadinho (Feijão Dam 1) tailings dam in Brazil where 270 people were declared dead or missing following the discharge of 43mln m3 of mud clearly do not help the mining industry's image (Rotta et al. 2020). Against this sort of backdrop, the mining industry must work harder at marketing both the need for mining to provide the raw materials to achieve Net Zero globally, and also just what it is doing to promote and achieve better environmental standards within the mining industry.

Rio Tinto and BHP illustrate the way forward

The largest mining companies are rapidly developing their environmental credentials. Rio Tinto's investor seminar in December 2023 (Rio Tinto 2023d) and its 2023 results presentation (Rio Tinto 2024c) held examples of what the company is doing and how Rio Tinto aims to achieve its targets.

Others have similar undertakings. For instance, BHP (2023b, 2024e), the world's largest mining company, outlined its approach to operational decarbonisation in a presentation dedicated to this aim. The company says that it is on track to reduce operational emissions by at least 30% in its 2030 financial year (year to 30 June 2030) compared with FY2020 levels and has an aspirational goal of Net Zero emissions in 2050. To date operational greenhouse gas emissions are 32% lower than the baseline 2020 year. Much of this has been achieved through introducing renewable electricity at many of its operated assets. Looking forward, BHP plans to replace its diesel-powered water boilers used in electrowinning copper in Chile with thermo-solar energy. More significant will be the transition of the haul-truck fleet from diesel-mechanical to diesel-electric through trolley-assist, and then to zero emissions by way of autonomous trolley-assist battery powered trucks which BHP hopes to complete in Chile by 2040. Figure 14 illustrates the company's Net Zero trajectory.

Figure 14 - BHP's operational decarbonisation trajectory



Source: BHP 2023b

Cross-industry collaboration

BHP, Rio Tinto and other leading mining companies are looking at additional solutions working both together and with equipment suppliers and technology providers. A good example is the Komatsu Greenhouse Gas (GHG) Alliance which is looking at various haul-truck power options including trolley-assist battery power. The Komatsu (2023) alliance can count on some of the world's largest mining companies amongst its membership, including Rio Tinto, BHP and Codelco. This collaboration has been extended in Western Australia's Pilbara iron ore mining industry with BHP, Rio Tinto, Caterpillar and Komatsu collaborating on battery-electric haul truck trials to support both mining companies' ambition to reach Net Zero operational greenhouse gas emissions by 2050 (BHP 2024c).

Another key collaboration, set up almost four years after the Brumadinho tailings dam disaster was the launch, in early 2023, under the auspices of the United Nations Environment Programme (2023) and the Church of England Pensions Board (representing the Principles for Responsible Investment group) of the Independent Global Tailings Management Institute (GTMI). This has been set up to oversee the implementation of, and conformance with, the Global Industry Standard on Tailings Management. Collaborations such as the two highlighted above are key to fast-tracking initiatives for the common good.

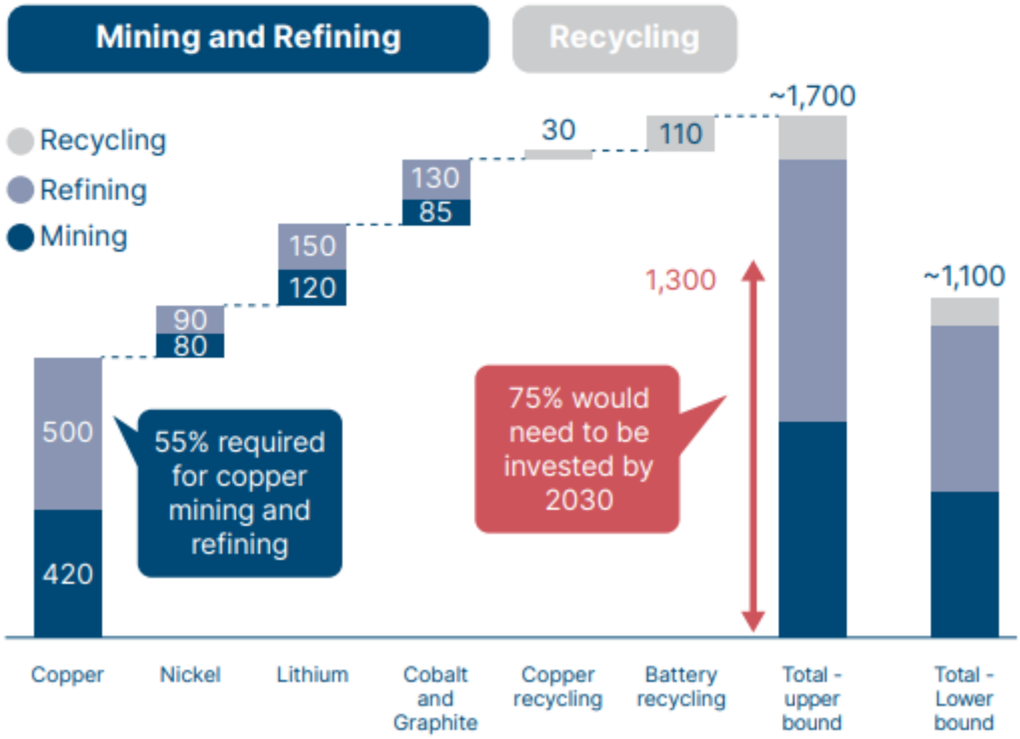
The mining industry needs to market its environmental credentials better

The mining industry needs to market itself much more actively to demonstrate how it is planning to achieve Net Zero at least with regards to Scope 1 emissions (those that are generated within the company) and Scope 2 emissions (indirect emissions, such as purchased electricity, for instance). By achieving this, the mining industry will also help to reduce overall Scope 3 emissions (those emitted up and down a company's value chain i.e. from its suppliers and by its customers too).

Financing challenges

A review entitled 'Material and Resource Requirements for the Energy Transition', published by the Energy Transitions Commission (2023), suggests that, depending on the demand scenario, US$1.1-1.7 trillion of investment will be required between 2021-2050 to fulfil demand for the mining, refining and recycling plants required to provide adequate supply of cobalt, copper, graphite, lithium and nickel (Figure 15). Of this total, US$480-750mln relates to mining. Approximately 75% of this investment will be required in the next decade, at around US$70bln pa, which is about US$25bln pa more than average spending levels of the last decade.

Figure 15 - Investment requirements for CRMs for the energy transition 2022-2050 (US$bln)



Source: Energy Transitions Commission 2023

On a similar theme, UN agency UNCTAD (UN Trade & Development 2024) estimates that demand for critical energy transition minerals like lithium, cobalt and copper could increase by almost fourfold by 2030 and by over 1,500% by 2050. The agency has identified 110 new mining projects worldwide, but believes that to meet Net Zero emission targets in 2030 we need around 80 new copper mines, 70 new lithium and nickel mines each, and 30 new cobalt mines. Another study by the International Energy Forum (2024), estimates that, depending on the 'green' scenario, we will need between 35 and 194 new copper mines by 2050, each of 472,000tpa copper production (the average production rate of the 10 largest copper mines in 2022). Furthermore, UNCTAD (2024) estimates that to meet its new mine projections would require an investment of between US$360bln to US$450bln between 2022 and 2030, leaving a potential investment deficit of between US$180bln and US$270bln. Another recent study, by the International Energy Agency (2024c), suggests that under its Announced Pledges Scenario and its Net Zero Emissions scenario total capital requirements in new mining investments could be as high as US$590bln and US$790bln respectively, with US$330bln and US$490bln required for copper under the two scenarios, US$130bln to US$160bln for nickel and around US$80bln under both scenarios for lithium.

Weak exploration spending

This issue is exacerbated by relatively low exploration expenditures. Estimates from S&P Global Market Intelligence (2023 a & d) suggest that while aggregate global non-ferrous exploration expenditure in 2022, at US$13.1bln, was at its highest levels since 2013, it is still well below the record level of US$20.5bln reported for 2012. Estimates for 2023 (S&P Global Market Intelligence 2024d) suggest a further decline of almost 3% to US$12.76bln with current weakness in both metal prices and financing suggesting weakness continuing into 2024 - S&P Global Market Intelligence (2024d) anticipates a probable 5% decline, i.e. to around the US$12.1bln level.

The general impact of global economic recession together with high inflation, higher interest rates and increases in energy prices, as well as the trend towards greater government intervention towards mining projects, means that expenditures in 2023-2030 (at least in the first couple of years) for exploration, mining, refining and recycling are very unlikely to reach the US$80-100bln pa that we believe may be required globally if we are to satisfy demand across all CRMs.

Huge finance needed downstream too

If we are to achieve Net Zero in a sensible time frame then huge investment is also needed to build electric vehicles, wind turbines and so on. Jaguar Land Rover (JLR) recently announced it would build its flagship gigafactory in the UK, the largest automotive investment in the country since the 1980s. Tata (the owners of JLR) will invest £4bln (US$5.25bln). The 40GWh gigafactory is expected to start production in 2026, and will provide nearly half the EV batteries needed in the UK by 2030 according to the UK government (2023). Savannah Resources (2024) notes that plans for around 1.2TWh of gigafactory capacity have been announced across Europe up to 2030, and assumes that c.70% of this or 0.8TWh will materialise by 2030, requiring 680,000tpa of LCE. Assuming the same capital intensity as the JLR gigafactory, then US$105bln will need to be spent to achieve 0.8TWh of capacity and US$157.5bln to achieve 1.2TWh in Europe alone. If one considers the capital requirements across the globe for all of the downstream developments needed to satisfy Net Zero we must surely be talking about trillions of dollars.

Sourcing finance and national government initiatives

If the world is to meet Net Zero between 2050 and 2060, Levin et al. (2023) suggest that global greenhouse gas emissions will need to drop by nearly half by 2030. McKinsey Global Institute (2022) estimates that capital spending on physical assets for energy and land-use systems between 2021 and 2050 would amount to about US$275 trillion, or US$9.2 trillion on average each year, which is US$3.5 trillion pa more than 2021 levels. To achieve this we will need real public-private partnerships to finance and fast-track this progress; transformational policies will be required and time is not on our side.

Initiatives from global organisations

Some financing initiatives will be by way of global organisations, such as the Mandate Letter recently signed by the International Finance Corporation (the private sector arm of the World Bank) to provide a senior debt facility of US$91mln to NextSource Materials (2024) for the expansion of its Molo graphite mine in Madagascar. But by far the majority of these initiatives will need to be from national government initiatives.

Government initiatives improving in the UK

The recent JLR gigafactory announcement will be supported by the UK government. Various government initiatives like the Automotive Transformation Fund, the Advanced Propulsion Centre and British Industry Supercharger, may be involved, according to the UK government (2023). Governments, however, have a checkered history of support. In 2021, Britishvolt, a start-up company, announced plans for a £3.8bln 30GWh-capacity (2030) gigafactory to be built in Cambois, Northumberland, in northern England. However, development work was halted in August 2022 and the company collapsed in January 2023 following funding issues, notwithstanding the UK government's offer of a grant of £100mln which was conditional on securing battery manufacturing equipment from Germany and Korea. Had the UK government provided funding via a 'soft loan' and not linked it to equipment purchase, Britishvolt could now be at the development stage. Instead, Britishvolt has been bought out of administration by an

Australian start-up, Recharge Industries, but funding to restart development has still to be secured (Wikipedia (2) 2024, Financial Times 2023, Guardian 2022). The administrators are seeking new buyers since Recharge Industries is apparently in default (ITV 2024).

But perhaps the UK (and other governments) are learning. One of the most recent examples of UK government support is from the UK Infrastructure Bank (2023), which in an interim form was set up in June 2021. The ambition of this government-owned but independently run bank is to provide £22bln of infrastructure finance to tackle climate change, support regional and local economic growth across the UK and to help the country achieve Net Zero by 2050. Recently, the bank announced its first equity investment, c.£24mln (US$30M), in Cornish Lithium, a privately-owned company with both hard rock and geothermal brine lithium projects in Cornwall, England.

Another example of help in the UK is the Saltend Chemicals Park, where Pensana (2021) is developing a Rare Earths Processing Hub as part of the Humber Freeport, giving Pensana business rates relief for the first five years of operation, National Insurance relief for new employees, discounts on land tax and stamp duty, 130% deduction for main pool assets and 100% deduction for special pool assets. In late 2023, it was announced that the UK government would offer a grant of up to £4mln towards funding Pensana's facility at the Humber Freeport (Pensana 2023a).

More recently, Pensana issued an update on its financing, and this provides a good illustration of private/public financing structures. Following a modular re-design of its Longonjo REEs mine and processing facility in Angola, the company has now released an updated capital cost estimate (which includes a US$20mln contingency) of US$217mln (Pensana 2024a). This will be funded by a project finance debt facility of up to US$156mln with a lender consortium (Pensana 2024b) and US$80mln of equity (this ratio is a fairly typical debt:equity split). South Africa's ABSA Bank will be the lead arranger of the loan facility and has already provided high level commercial debt terms which include South African export credit agency support. FSDEA (Angola's sovereign wealth fund) and 'a pan-African multi-lateral development financial institution' are working to provide the US$80mln equity investment (FSDEA has already provided a US$15mln bridging loan facility as part of this US$80mln to provide operating cash flow requirements). Work is underway on an updated Mineral Investment Contract which could see a reduction in the corporate income tax rate for a period of 15 years, deferral of tax payments for six years, investment tax reduction (applicable to profit and dividend distribution) for 15 years and an investment premium (uplift) corresponding to the cost recoverable and tax deductible in terms of the investment to be made for mining and product marketing.

The US$250M capital expenditure for the Saltend REEs separation facility will be funded by US$150mln from institutional clients of ABG Sundal Collier via a bond which has received green bond accreditation from Shades of Green (part of S&P Global) and US$100mln of equity (so again a fairly typical debt:equity mix) from potential equity partners that may include the UK Infrastructure Bank. And of course there is the £4mln grant that has already been offered.

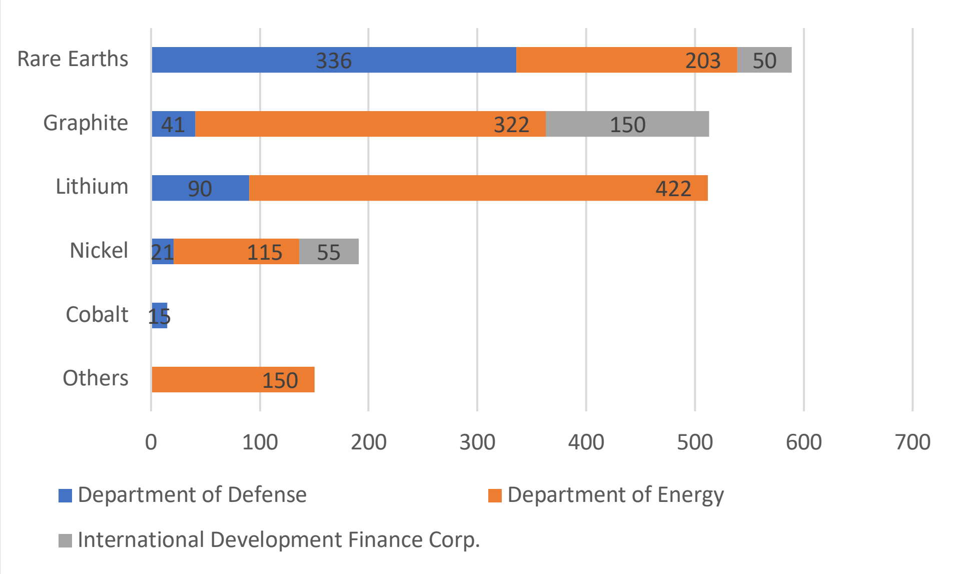
Changes in government can also lead to significant changes in national resources policy, for better or worse. The July 2024 landslide victory for the Labour Party in the UK, for instance, has ushered in the likelihood of two new developments, as outlined in the party's election manifesto (Labour Party 2024). The first is the proposed creation of a new publicly-owned company, Great British Energy, which will be capitalised with £8.3bln over the next Parliament and 'will partner with industry to deliver clean power by co-investing in leading technologies (and) will help support capital-intensive projects…and build supply chains…'. There is no detail, but if this includes supporting the development of the mining and processing of energy raw materials (such as the Cornish Lithium and Pensana initiatives outlined above) then this should be welcomed. The second manifesto initiative involves the establishment of a National Wealth Fund (as seen in a number of other countries such as Norway) which will be capitalised at £7.3bln over the next Parliament. One of the initiatives specifically outlined is £1.5bln for new gigafactories for EV batteries, which again could indirectly benefit the development of CRMs within the UK, and by British companies overseas.

Support to national governments can also be assisted by trade and other organisations, such as the March 2024 initiative by the UK's Institute of Directors, an organisation of UK business leaders, which has launched a Natural Resources Special Interest group to support sustainable development of natural resources (Mining Journal 2024g).

The US IRA and other government initiatives

Other governments are even more ambitious than the UK government (though of course the economies that they service may be a lot larger than others). For instance, in the USA the Department of Energy has made a conditional commitment for a loan of up to US$700M to Ioneer's Rhyolite Ridge lithium-boron project in Nevada (Ioneer 2023). The US has three government departments or agencies funding CRMs projects. The Departments of Defense and Energy have funded domestic projects, primarily in REEs, and lithium and graphite, respectively, while the International Development Finance Corporation, which is overseen by the Secretary of State, can invest in projects in 'friendly' countries, and has focused on graphite, REEs and nickel (Figure 16). According to the Mining Journal (2024f), and as illustrated in Figure 16, together these three entities have invested US$1.97bln in (publicly announced) mineral extraction/processing projects since October 2020, over 80% of which has gone into REEs (US$589mln), graphite (US$513mln), and lithium (US$512mln). Other US state entities also invest. For example, in April 2024 the Export-Import Bank of the United States (EXIM), the country's official export credit agency, signed a Letter of Intent to provide up to US$3.5M of US export contracts for GreenRoc Mining's Amitsoq graphite project in Greenland and/or an active anode processing plant and followed this up, in July 2024, by signing a non-binding indicative termsheet with Quantum Graphite and Sunlands Energy for a financing commitment of up to US$300M for the Uley graphite project (South Australia) and high-purity graphite processing plant in the USA (probably in South Carolina), subject to confirming certain logistics requirements (GreenRoc Mining 2024, Quantum Graphite 2024).

Figure 16 – US government critical minerals funding totals almost US$2bln



Source: Mining Journal 2024f

On a broader and bigger platform, and as noted by S&P Global Market Intelligence (2023c), the US Inflation Reduction Act (IRA) was passed in 2022 which, as part of a wider suite of energy transition and infrastructure spending, adds up to almost US$1 trillion of spending capacity. Specifically, the act provides a 10% subsidy for a range of CRMs production costs and a consumer subsidy of up to US$7,500 for EV purchases subject to certain local content/free trade agreements relating to supply chain considerations for critical minerals, batteries and vehicles (Energy Transitions Commission 2023). S&P Global Market Intelligence (2023c) estimates that US energy-transition demand for lithium will be 15% higher by 2035 than was projected pre-IRA, with increases of 14% for nickel, 13% for cobalt and 12% for copper on the same basis.

Another example of government assistance is the recent €902mln German measure to support Northvolt in its development of a gigafactory in Germany. In the press release announcing its approval, the European Commission (2024a) specifically notes that without this aid Northvolt would establish the battery plant in the USA instead, supported by the Inflation Reduction Act.

More recently, in February 2024, and in a move that shows that CRMs availability is not just an issue for major developed nations, Brazil announced that it is launching a US$200mln critical minerals fund with the ambition of investing in 15-20 junior and medium-sized mining companies (Mining Journal 2024c).

Meanwhile, in May 2024 the Australian government (Australian Minister for Resources and Minister for Northern Australia and the Prime Minister of Australia 2024) announced, as part of a big focus on resources in the 2024 Budget, an A$566.1mln initiative over 10 years from 2024-25 to deliver data, maps and other tools for the resources industry led by the Geoscience Australia government agency.

May 2024 also saw an announcement from EIT RawMaterials (2024), which is co-funded by the European Union, and mandated by the European Commission to lead and manage the European Raw Materials Alliance. The organisation announced €100mln of new funding for high-impact projects in the European raw materials sector to add to the €200mln expenditure already underway over the 2023-2025 period. This was followed, in July 2024, by the launch of a joint equity investment facility by the European Bank for

Reconstruction and Development (2024) and the European Union for critical raw materials. The EBRD and the EU are each contributing €25M with plans to mobilise a further €50mln.

These examples show the different forms that government financial support can take and while all are laudable, much, much, more is required across the globe. It would help if 'friendly' governments could work together in supporting the move to global Net Zero rather than competing against one another.

Lack-of-awareness of how acute the issue is

While most governments, companies and people are aware of and accept that the human race is at least a contributor to Climate Change, if not solely responsible, there are still some that do not accept this. Even amongst those that accept our role in Climate Change, there is, as the Energy Transitions Commission (2023) points out, very low awareness and acknowledgement of the need for increases in CRMs mine production to achieve energy transition.

In a Policy Paper, the Institute of Materials, Minerals & Mining (2024) notes that if we are to meet the global demand for critical materials five key challenges need to be overcome; a significant expansion of responsible mining, decreased usage, drastic increases in recycling, design for end-of-life and closed loop cycling of polymers/composites.

The lack-of-awareness of the criticality of our CRMs requirements is widespread; amongst government officials, financial and private sectors and especially the general public. There is also very little awareness that this will not only require a substantial increase in mining globally to provide these minerals, but also an increase in downstream semi-finished or component manufacture.

An example: the challenge for Europe in lithium

To illustrate the challenge, let's look at the European Union, which in March 2023 proposed the European Critical Raw Materials Act (European Union 2023a) and adopted the regulation 12 months later (European Union 2024). This sets the EU 2030 benchmarks for strategic raw materials; to extract at least 10% of annual consumption, process at least 40% of annual consumption, supply at least 15% of annual consumption from recycling and ensure that no more than 65% of the EU's annual consumption of each strategic raw material at any relevant stage of processing comes from a single third country.

IMERYS (2022) estimated that Europe will require 600,000t of lithium carbonate equivalent (LCE) by 2030 but it estimated that European lithium extraction projects will only be around 250,000t LCE by then, or 42% of the required total. Table 5 shows that the most advanced lithium mining/brine projects in Europe that are slated to be developed between 2025 and 2030 could have a capacity of 321,000tpa LCE (the EU, Serbia and the UK), representing 54% of Imerys' 2030 demand (company websites (4) 2024). This figure is clearly higher than the Imerys estimate, which is a few years old. The figure appears to be comfortably ahead of the EU target of 10% or 60,000t (based on the demand forecast made by Imerys).

Table 5 – EU, Serbia & UK - potential lithium mining/brine production capacity by 2030

Potential start-up	Operation	Operator	Country	Capacity ktpa LCE
2025	Keliber	Sibanye Stillwater	Finland	13.2
2025	Wolfsberg	European Lithium	Austria	7.7
2026	Zero Carbon Energy (Phase 1)	Vulcan Energy Resources	Germany	21.1
2026	Barroso	Savannah Resources	Portugal	26.0
2026	Zinnwald	Zinnwald Lithium	Germany	10.6
2026	San Jose	Infinity Lithium	Spain	29.0
2026	Cinovec	CEZ/European Metal Holdings	Czechia	25.9
2026	Trelavour	Cornish Lithium	UK	6.9
2027	Lauterbourg (Phase 1)	Viridian Lithium	France	25.1
2028	EMILI	Imerys	France	29.9
2028	St. Austell	Imerys	UK	21.0
2028	Jadar	Rio Tinto	Serbia	58.0
2029	Zero Carbon Energy (Phase 2)	Vulcan Energy Resources	Germany	21.1
2030	Lauterbourg (Phase 2)	Viridian Lithium	France	25.1
	TOTAL			320.6

Source: company websites (4) 2024, author. Conversion – 1t lithium hydroxide = 1.543 t lithium carbonate equivalent (LCE) and 1t lithium hydroxide monohydrate = 0.88t lithium carbonate equivalent (LCE)

However, this would imply that all projects proceed on time and to budget – and most of them have not yet cleared all permitting and/or internal approval and financing processes. To illustrate the challenge, let's look at Savannah Resources, which hopes to build a spodumene lithium mine at Barroso, Portugal. According to its first Scoping Study in 2018 (Savannah 2018), production was expected to commence in Q1 2020, at a capacity of 175,000tpa of spodumene concentrate (SC) and an initial capital expenditure of US$109mln (excluding contingencies). But based upon the company's recent comments (Savannah 2023 & 2024) the current estimate is for a 2026 start-up, and while expected production rates have increased to an average of 191,000tpa of SC, initial capital expenditure has jumped to US$236mln excluding contingencies and US$280mln including contingencies though the company does point out that this figure includes US$40mln of 'community-related measures'. The key delays relate to getting environmental approvals. The point here is that while the tonnage from European extraction appears to comfortably beat the implied 60,000t target further delays to projects might mean that these projects fail to even achieve this 10% target.

The same challenge is true of the EU's 40% processing benchmark. Almost all of Europe's miners and brine producers also intend to add value downstream by producing battery-grade lithium hydroxide or carbonate. Table 6 highlights the most advanced European projects which could have a combined capacity of 579,000t LCE by 2030 (company websites (5) 2024), close to Imerys' European 2030 demand estimate of 600,000t. But again, many of these projects still seek funding and approvals, and some are still developing technology. Others are modular, so development to ultimate capacity may not proceed as currently envisaged. So again, it is quite feasible that with delays the 40% target i.e. 240,000t of Imerys' 600,000t demand estimate in 2030, will not be met.

It's also worth pointing out that others see an even bigger challenge. AMG Critical Materials, for instance, anticipates an annual shortfall in the EU of over 700,000t LCE by 2030 (AMG Critical Materials 2024).

The key point is that theoretically, the EU's criteria for the mining and processing of lithium could be met, but it will depend upon being able to provide the correct planning, financing and development environment to allow this to happen. As a result, estimates and commentary can be expected to range from those that believe that there is no issue in achieving Europe's lithium needs, to various stages of concern, based upon one's assumptions on project progress.

Table 6 – EU, Serbia & UK - potential lithium hydroxide/carbonate production capacity by 2030

Potential start-up	Operation	Operator	Country	Capacity ktpa LCE
2024	Bitterfeld-Wolfen (Phase 1)	AMG Lithium	Germany	17.6
2025	Keliber	Sibanye Stillwater	Finland	13.2
2025	Wolfsberg	European Lithium	Austria	7.7
2026	Zero Carbon Energy (Phase 1)	Vulcan Energy Resources	Germany	21.1
2026	Estarreja	Neometals/Mineral Resources	Portugal	22.0
2026	Zinnwald	Zinnwald Lithium	Germany	10.6
2026	San Jose	Infinity Lithium	Spain	29.0
2026	Cinovec	CEZ/European Metal Holdings	Czechia	25.9
2026	Wilton (Phase 1)	Alkemy Capital	UK	21.1
2026	Guben	Rock Tech	Germany	21.1
2026	Aurora	Galp/Northvolt	Portugal	30.8
2026	Teesport	Green Lithium	UK	44.0
2026	Trelavour	Cornish Lithium	UK	6.9
2027	Bitterfeld-Wolfen (Phase 2)	AMG Lithium	Germany	17.6
2027	Emden (Phase 1)	Livista Energy	Germany	36.4
2027	Lauterbourg (Phase 1)	Viridian Lithium	France	25.1
2028	EMILI	Imerys	France	29.9
2028	St. Austell	Imerys	UK	20.0
2028	Emden (Phase 2)	Livista Energy	Germany	36.4
2028	Jadar	Rio Tinto	Serbia	58.0
2029	Wilton (Phase 2)	Alkemy Capital	UK	21.1
2029	Zero Carbon Energy (Phase 2)	Vulcan Energy Resources	Germany	21.1
2029	Bitterfeld-Wolfen (Phase 3)	AMG Lithium	Germany	17.6
2030	Lauterbourg (Phase 2)	Viridian Lithium	France	25.1
	TOTAL			579.3

Source: company websites (5) 2024, author. Conversion – 1t lithium hydroxide = 1.543 t lithium carbonate equivalent (LCE) and 1t lithium hydroxide monohydrate = 0.88t lithium carbonate equivalent (LCE)

We are finally beginning to see signs of growing awareness amongst politicians not only of the need to satisfy domestic requirements for achieving adequate supply of CRMs, but also the urgency with which action is required. In the UK, the House of Commons Foreign Affairs Committee, in December 2023, clearly stated that the UK government's 'Critical Minerals Strategy does not convey the sense of urgency and need for immediate, decisive action which is of paramount importance if the UK is to deliver on its net zero commitments and enhance its long-term economic resilience in the face of mounting challenges'. Politicians in other countries are also slowly beginning to understand the urgency, but the general public are still woefully ill-informed.

Government initiatives and incentives

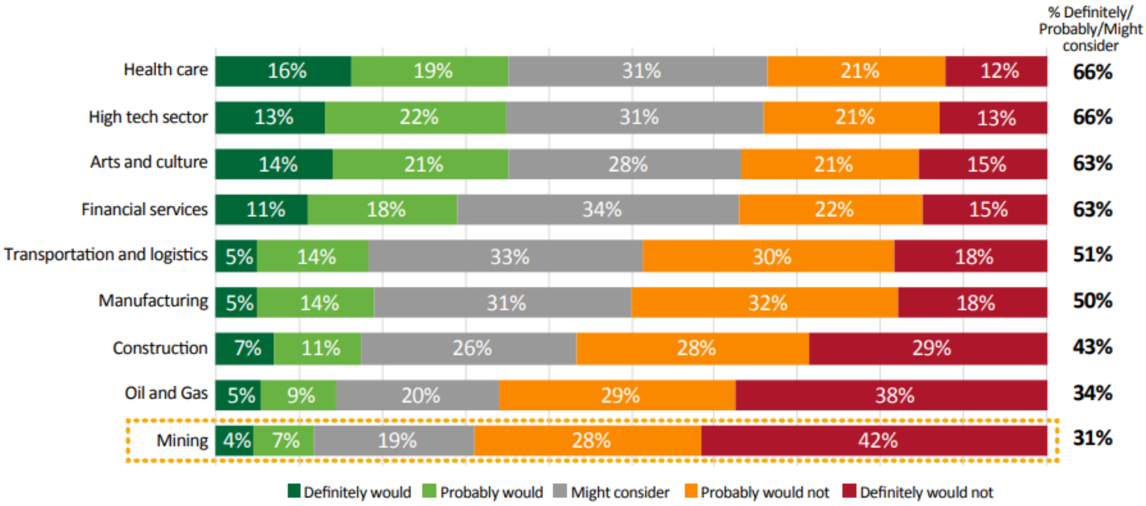
Governments can do a lot more to incentivise and promote CRM production. First, of course, is a consistent approach to policies that control planning, permitting, taxation and royalties, and as noted before these must take into account the interests of local communities and regional governments. In December 2023 the International Energy Agency (2023c) published guidance for policy makers to ensure sustainable and responsible critical mineral supply chains. The report outlines five key recommendations for policy makers. These include ensuring robust legal and regulatory protections (for the environment, workers and communities), channelling public spending to encourage better work practices (and reward good actors), strengthening the collection of benchmarking data in the mining industry and throughout the supply chain, improving transparency throughout the supply chain, and supporting the development of voluntary sustainability standards. These five recommendations may be laudable, but the pressing issue is the practical one – aiding and supporting the implementation of good working practices that promote CRMs supply.

In particular, it is on the financing front that governments need to be more willing to assist by providing loans, grants and tax-free zones, and by considering other tax and royalty breaks to help incentivise development of CRMs.

Labour challenges

One area where there is no quick fix is the acute skilled labour shortage which has impacted the mining industry worldwide. This is not a new phenomenon; it has become an increasing challenge for over a decade, but has become more pronounced since mid-2021. One of the catalysts is the slump in mining capital expenditure which peaked at US$164bln in 2012 (a year after metal prices hit all-time highs in 2011), falling to US$66bln in 2016. The Mining Journal (2023b) notes that between 2008 and 2012, 68% of mining engineering graduates in Australia found work in the mining industry or related consultancies, government roles or research industries, but between 2013-2017 only 38% of graduates were able to do so. In Australia, Canada and the USA four-year mining engineering degrees peaked in 2016 at 1,077 but had almost halved to 562 in 2020, and presumably continue to fall given the continuing trend of declining enrolments. In other parts of the world, the skills shortage is, and is likely to remain, even more acute. For all the recent political talk in the EU and the UK promoting greater self-sufficiency in critical raw materials, QS (2024), in its 'World University Rankings by Subject 2024', ranks only 7 of the world's top 40 universities for minerals and mining engineering in the region.

Figure 17 – Young Canadians (15-30) reject a career in mining



Source: Mining Industry Human Resources Council 2021

Mining seen as unattractive

In December 2020, a survey of young Canadians (15-30 years old), when asked what sectors they would consider working in, responded very negatively to mining; 42% said that they would definitely not, and 28% that they would probably not, consider working in the mining industry - the worst response of all sectors (Mining Industry Human Resources Council 2021). Compare that with the popularity of healthcare, high tech, arts and culture, or financial services (Figure 17). A recent review of 7 industry experts (Mining Journal 2024a) put 'attracting new talent' as the biggest priority for the mining industry over the next 10 years. Given the poor image that the mining industry has it's hard to see where it is going to find sufficient numbers of skilled workers to meet ambitions of increasing minerals self-sufficiency within a realistic timeframe.

Women significantly underrepresented

Women are particularly under-represented in the mining industry. The World Economic Forum (2021) notes that women represented just 12% of the workforce (in 2019), the second lowest of any sector, and ahead only of the construction industry. There is the latent potential for this proportion to increase, but poor industry image is likely to ensure a significant imbalance between men and women for a very long time; the industry will need to work very hard to challenge sexism in mining and redress the industry's image. The Mining Journal (2024e), in a concerning overview and sourcing data from multiple other sources, notes that energy and mining is the second worst industry (after construction) for women in leadership and in the workforce in general and the worst for board participation, while there is a failure to advance women into middle management. One-fifth of women in the mining industry want to leave due to the lack of growth opportunities.

The lack of sufficient geologists, mining engineers and metallurgists, and gender inequality, is an aspect that is generally overlooked globally, and is not something that can be rectified in the short-term. Much more needs to be done if we are to have enough skilled workers and management in the industry.

Potential job losses

While we all focus on the benefits of achieving Net Zero, there is also a downside that is overlooked by most people. The oil and gas industry directly employs six million people, and indirectly is responsible for more than 60 million jobs worldwide, according to the International Labour Organization (2024). Clearly a major reduction in the use of oil and gas is likely to lead to significant job losses. This issue is also expected to impact the other fossil fuel, coal. Tate et al. (2023) estimate that 414,000 workers are employed in coal mines that are set to close by 2035, and by 2050 global job losses in the coal mining industry are expected to total one million, many of them in China and India, and 242,000 in China's Shanxi province alone. The energy transition may bring with it substantial unanticipated socio-economic repercussions.

Financial market challenges – higher interest rates, lower equity raisings

Commercial lenders and equity investors will only invest in a business if they can expect a return; and the higher the risk in an investment, the higher the reward targeted. Here, the motive differs from that of a government or another company. Governments may be more interested in job creation or infrastructure development while manufacturing companies may be more interested in securing raw material supply.

Economic slowdown, recession or near-recession, the jump in inflation and interest rates and slow recovery post COVID-19 have impacted all countries and companies, but to varying degrees. For the largest mining companies, their ability to raise debt has not really been impacted; all that has changed is the coupon. For instance, in October 2021, Rio Tinto's US finance subsidiary issued US$1.25bln of 30-year fixed rate notes with a coupon of 2.75%. Fast-forward 18 months to March 2023 and the same unit raised US$1.1bln of 30-year notes with a coupon of 5.125% and a further US$650mln of 10-year notes with a 5.0% coupon (Rio Tinto 2021, 2023b).

Table 7 – Mining equity fundraisings slump in 2022

2021	2022	Change	
Secondary fundraisings	US$20.38bln	US$12.11bln	-41%
No. of secondary fundraises	2,094	1,664	-21%
Initial public offerings	US$1.83bln	US$976M	-47%
No. of IPOs	129	85	-34%
Total equity raised	22.21	13.09	-41%
Total no. of offerings	2,223	1,749	-21%

Source: Mining Journal 2023a

Equity offerings are weak

2022 was a poor year for mining equity fundraising as economic slowdown and the Russian invasion of Ukraine bore down on share prices and investor sentiment. As illustrated in Table 7, the Mining Journal (2023a) notes that secondary fundraising slumped 41% from US$20.38bln in 2021 to US$12.11bln in 2022 while the number of secondary raisings fell from 2,094 to 1,664. Initial public offerings (IPOs) fell by an even greater amount, 47%, from US$1.83bln raised in 129 IPOs in 2021 to US$976mln from 85 IPOs. S&P Global Market Intelligence (2024b) suggests that equity fundraisings for junior and intermediate companies fell further in 2023, to around US$10.4bln, the lowest level since 2019.

The situation is most acute for junior exploration companies who, by definition, struggle with cash burn and frequently require additional funding to continue their exploration programmes. The significance here is that in many countries juniors contribute a major proportion of exploration spending and are responsible for a significant proportion of discoveries. Between 2012 and 2021, juniors accounted for 63% of all discoveries in the Western World (and 73% in Australia) (Schodde 2023). This is partly a function of M&A amongst the majors (i.e. there are fewer companies as a result of M&A, and their exploration budget post-merger is usually lower than the sum of the two individual budgets pre-merger), and also a shift in exploration risk and expenditure by the majors moving from a greater proportion of own-exploration to an increased reliance on joint ventures with juniors. The problem for junior explorers though, is you need cash inflows to finance your initial exploration programme to advance it to the point where the majors are interested in buying into the juniors' exploration programmes.

Lack of terminal market pricing doesn't help, nor does pricing volatility

Investors like clarity and one issue is that for many CRMs, markets are small, and pricing is opaque. By comparison, base metals and precious metals markets are large, with significant turnover and terminal markets, like the London Metal Exchange (LME) or the London Bullion Market Association (LBMA), that provide a clear source of pricing. The LME, for instance, provides contract specifications for each metal, allowing consistent pricing for spot, forward, options and futures contracts based on a defined chemical composition. Bulk commodity markets are also large, but because the products are not homogenous, pricing varies, although benchmark prices are generally readily available. For iron ore, price will depend on whether the ore consists of fines or lump, the iron content, and which impurities (such as phosphorous) are present. For coal, pricing will depend on whether it is thermal coal (for power generation) or coking coal (for steelmaking), with pricing varying for quality issues like calorific value, moisture, ash and sulphur content. Benchmark prices are available for coal and iron ore in specialist trade journals. However, with smaller markets and opaque pricing, CRMs investments may be harder to value, and this can therefore deter potential investors. Fortunately, there are a number of consultants and research houses that are beginning to create pricing streams for CRMs. One example in lithium, for instance, is Benchmark Mineral

Intelligence (2024) which provides 9 global lithium carbonate prices, 6 lithium hydroxide prices, one spodumene concentrate price and also derives global averages weighted by volume for lithium carbonate and hydroxide.

Small markets are volatile, repercussions can be huge

The other key challenge for investors, exacerbated in relatively small commodity markets with opaque pricing, is that these markets can be highly volatile and easily influenced by extraneous factors as well as by traditional, but sometimes swift, changes in supply and demand dynamics. One might argue that, for instance, the lithium mining industry was too successful in bringing additional supply onto the market in 2023. As a result, the lithium carbonate price (China, 99%) peaked in November 2022 at over US$82,600/t and fell by over 85% through 2023, to start 2024 at prices just over US$12,000/t. Given a lithium supply surplus of 95,000t LCE in 2023 and a further surplus of 100,000t estimated for 2024, lithium prices could weaken further this year (S&P 2024a & c), and currently stand at just over US$10,000/t.

The impact of current lithium pricing levels (while significantly higher than the troughs of c.US$5,000/t experienced in 2020) have been exacerbated by the rate at which the price fell through 2023, making planning and financing a challenge. In January and February 2024 we have seen a host of corporate announcements that illustrate the dilemma companies are in. On the production front, these include plans to reduce (IGO 2024) or suspend mining (Core Lithium 2024). Others have announced plans to reduce operating costs and capital expenditure (Albemarle 2024a, Piedmont Lithium 2024), have issued significant profit warnings (Ganfeng Lithium 2024, Tianqi Lithium 2024), decided to focus on cash preservation via dividend suspension or devlopment slowdown (Pilbara Minerals 2024a, Galen Lithium 2024) and have seen the suspension of proposed project financing due to commodity price decline (Liontown 2024a). With lithium prices back around three-year lows in mid-2024, the announcement of study results that could double Pilbara Minerals' (2024b) annual spodumene concentrate production to 2mln tpa would appear unhelpful. These lithium market examples illustrate the short-term challenges faced by the mining industry in ensuring sufficient supply of CRMs, but also impact longer term planning and financing paradigms.

High commodity prices do not always offer protection

It is also worth noting that just because a commodity is trading near record highs – in May 2024 copper achieved a record price of around US$5.20/lb – that does not always offer financial protection. For instance, Nevada Copper, operator of the Pumpkin Hollow underground copper mine in Nevada, ran into technical challenges in 2022 as it was ramping-up production (Nevada Copper 2022). Having initially received financial support from its leading shareholders, and notwithstanding record copper prices, the company failed to ensure further finance and in mid-2024 Nevada Copper was forced to file for Chapter 11 bankruptcy protection Nevada Copper 2024a & b).

End-user investments

Another source of finance can come from the end users of CRMs. This is most obvious in the car industry, as automakers strive to ensure sufficient raw material supply as they grow their EV production. As Table 8 (located at the end of this paper) illustrates, the number of deals is significant, over 70 in total, and growing rapidly. Tesla was one of the first to get actively involved, but more recently Stellantis and Ford have been very active. Almost all of the major car manufacturers have posted aggressive EV manufacturing targets. The transactions may be via offtake agreements (which help the raw material supplier guarantee sales and help indirectly in generating finance) or via direct financing (equity or loan participation), or a combination of the two. Many of the deals are for EV battery raw material supply, and here battery makers like LG Energy Solution or Samsung SDI have done deals directly with mining companies as well as, or alongside, automakers. Automakers have also signed deals in related areas like battery technology and recycling, hydrogen fuel cells, geothermal energy, CO2-reduced 'green' steel and semiconductors.

Examples of automaker investments – Stellantis

Two of the more recent automaker – mining company transactions, both announced in October 2023, involve Stellantis, owner of 16 automotive brands including Fiat, Peugeot, Citroen, Chrysler and Opel. In early October 2023, the company reported a US$90mln investment in four Argentinian lithium exploration projects owned by Argentina Lithium & Energy (2023). The agreement includes the supply of 15,000tpa of lithium starting in 2028 for an initial period of 7 years. Then, on 11 October 2023, McEwen Mining (2023) announced that Stellantis would invest ARS42bln (US$120mln) in shares of McEwen Copper, primarily to advance the Los Azules copper project in Argentina. Meanwhile, an example of automaker – battery maker collaboration, also announced on 11 October 2023 and also involving Stellantis (2023), is that the Stellantis – Samsung SDI joint venture, StarPlus Energy, will build its second battery gigafactory in Indiana at a cost of over US$3.2bln.

Financial involvement by end-users is, however, largely restricted to EV automakers and battery manufacturers. There is little evidence of the same strategy elsewhere, however, so many CRMs explorers and mine developers are still struggling to secure finance. These mining companies must rely on traditional forms of financing.

Attracting large mining companies into critical raw materials production

Although exploration expenditure for CRMs is accelerating, there is still a strong bias towards gold and base metal exploration. The challenge for the mining majors is that the markets for CRMs are relatively small. For instance, based on global lithium production of 999,400t LCE in 2023 and the blended year-end 2023 price of relevant market indices (quoted by Albemarle 2024b) of US$15,000/t the global lithium market is worth c. US$15.0bln. Compared with that, Rio Tinto generated revenue in 2023 of US$30.9bln just from its Pilbara iron ore operations – double the global lithium market. It will take time for a major to build a meaningful earnings profile in a particular EV commodity like lithium or graphite, as well as money (including, potentially, premiums for acquisitions) and the acquisition of a new skill-set; mining, processing and marketing on a smaller, and more specialist, scale than for bulk commodities or base metals. To put this in perspective, the world's largest mining company, BHP, is capitalised at US$136.2bln, 14-times the size of Albemarle, the largest lithium producer (by market capitalisation), capitalised at US$10.0bln (4 September 2024).

However, the majors are beginning to show interest in critical raw materials. Rio Tinto is a good example, as can be seen from numerous news releases on the company's website (Rio Tinto (various) 2024e). The company has been mining boron in California since 1927 and discovered the Jadar lithium-borates project in Serbia in 2004. A news release in 2017, noting the signing of a Memorandum of Understanding between Serbia and Rio Tinto, spoke of a potential construction start in 2020 and operational start-up in 2023 (Rio Tinto 2017). Progress was slow and after environmental and local concerns the Serbian government cancelled the spatial plan for the project and revoked Rio's licence in 2022, though the company remained hopeful that the project may be able to resume if it can reach agreement with all stakeholders. The most recent developments follow the September 2023 signing of a letter of intent between Serbia and the European Commission on a strategic partnership in batteries and CRMs, including lithium, which suggests that the Serbian government would like to find a solution with Rio Tinto (Economic Intelligence Unit 2023) and then, post the December 2023 parliamentary elections in the country, Serbia discussed with Rio Tinto Rio's potential legal action against Serbia at the World Economic Forum in Davos in January 2024 (Mining.com 2024b). In June 2024 the Serbian President, Aleksandar Vučić, stated that 'new guarantees' from Rio Tinto and the EU looked set to address Serbia's environmental concerns (Financial Times 2024), potentially allowing mining to start in 2028. Then, in July 2024, the Constitutional Court of Serbia declared that the government's decision to halt the Jadar project in 2022 was unconstitutional (Balkan Insight 2024a). This was swiftly followed, just a few days later, by a memorandum of understanding signed at the Serbian Critical Raw Materials Summit in Belgrade between Serbia's Minister of Mining and Energy, Djedovic Handanovic, and the European Commission vice-president Maros Sefcovic covering sustainable raw materials and battery supply chains. Also present were German Chancellor Olaf Scholz, Rio Tinto's CEO Jakob Stausholm, and senior representatives of the European Bank for Reconstruction and Development, the KfW Group (a German investment and development bank), and automakers Mercedes-Benz and Stellantis as well as lithium battery-makers. It would appear that the development of Jadar will finally push ahead, though local and environmental opposition still remains (Balkan Insight 2024b, BBC 2024). Ultimately, the mine is expected to produce 58,000t of battery-grade lithium carbonate, 160,000t of boric acid and 255,000t of sodium sulphate annually (Rio Tinto 2024e).

Rio has been busy elsewhere in lithium too. In 2019, Rio established a demonstration plant in California to recover battery-grade lithium from boron wastepiles and in 2022 started a demonstration plant to produce spodumene concentrate in Quebec as well as making a US$10mln investment in Nano One, a Canadian clean technology innovator in battery materials. In 2022 the company also completed the acquisition of the Rincon (Argentina) direct lithium extraction project from Sentient Equity Partners for US$825M. Rio added to its lithium footprint in 2023 with a US$7.5mln earn-in agreement on Aterian's HCK project in Rwanda (Aterian 2023). More recently (November 2023), Charger Metals (2023) announced that Rio Tinto had signed a binding farm-in agreement on Charger's Lake Johnston lithium project in Western Australia, and SAGA Metals announced that Rio Tinto had signed a joint venture agreement on SAGA's Legacy (Quebec) lithium project (SAGA Metals 2024). Rio's lithium strategy has culminated with the October 2024 agreed US$6.7bn offer for Arcadium Lithium which will provide Rio with 75,000tpa LCE global production capacity, together with expansion plans to more than double this by 2028 (Rio Tinto 2024f).

Rio Tinto (2024e) also entered the scandium market in 2022, becoming the largest North American producer of high-quality scandium oxide with the construction of a commercial-scale demonstration plant in Quebec using titanium dioxide production waste streams and in 2023 announced the acquisition of the Platina scandium project in New South Wales for US$14mln from Platina Resources. In 2022, Rio also became one of only two US producers of the critical material tellurium as a by-product at its Kennecott copper refinery in Utah while in 2023 the company invested A$40.4mln in Sovereign Metals (a 15% position). The funds will be used to advance Sovereign's Kasiya rutile-graphite project in Malawi. Rio added a further A$18.4mln investment via option exercise in 2024 (Sovereign 2023 & 2024).

Many of these new initiatives have been created through Rio Tinto Ventures, a group established in 2017 to look at commodities beyond Rio's traditional portfolio and in new jurisdictions and new deal structures, either via majority or minority interests and either to be retained long-term or to add value and then sell-on. Rio has also developed its technology base to add potential mineral resources to its portfolio. For almost 30 years Rio Tinto has been researching direct copper sulphide leaching. The company hopes to monetise this through its Nuton business unit, and in 2022 and 2023 undertook investments in copper projects owned by Lion Copper & Gold Corp. (Nevada), Arizona Sonoran Copper (Arizona), McEwen Mining (Argentina) and Regulus Resources (Peru) (International Mining 2022, Regulus Resources 2023).

Further examples of creative thinking

Other mining majors are also trying to unlock the Holy Grail, the recovery of copper from low grade sulphide ores, both primary and secondary. BHP Ventures, as well as Freeport-McMoRan, Mitsubishi, Teck, BMW, investor T. Rowe Price and private equity company Orion Resource Partners, have all invested in and are working with Jetti Resources, one of the most advanced companies in this field; it is already implementing commercial trials. The total addressable market is huge; a 2021 study suggests as much as 234mln t of contained copper (Jetti 2021). BHP's Ventures unit has also recently invested in Ceibo, a Chilean company also developing a unique leaching technology for copper sulphide materials (International Mining 2023). Overall, BHP Ventures has 18 investments in junior mining and processing technology developers (BHP 2024b).

A more recent BHP initiative is the creation of BHP Xplor, an accelerator programme designed to support early-stage exploration for critical materials, providing both finance and access to BHP's expertise and partnerships (BHP 2024b). Nordic Nickel (exploring for nickel in Finland) participated in the inaugural programme (Nordic Nickel 2023), and BHP has recently announced the six exploration companies selected for a grant of up to US$500,000 each in the second cohort of the Xplor programme (BHP 2024a).

While these types of investments are very much a focus for the largest mining companies, they do demonstrate the latent potential to unlock significant additional CRMs. More investment, and an easing of the regulatory burden would, however, be welcome.

M&A activity to grow in critical raw materials?

We may also see an increase in M&A activity in the future. One of the key challenges that the largest mining companies have is that of 'buy vs build' and one way to shorten the timeframe required to build a position in a particular CRM is to buy your way in. To explore and add a meaningful set of assets to a corporate portfolio takes time, and no guarantee of success, and at certain points in the commodity cycle acquisition is seen as a preferred route. For example, in May 2023 BHP (2023a) completed the A$9.6bln acquisition of OZ Minerals, adding more copper and nickel to its CRMs portfolio, and in May 2024 BHP considered a US$49bln bid for Anglo American, again with copper as one of the key commodity targets. The plan was to return South African platinum (Anglo American Platinum) and iron ore (Kumba) shares directly to Anglo American shareholders. BHP subsequently decided no to proceed (BHP2024d). According to S&P (2024e) global mining M&A in 2023 reached US$26.36bln, the second highest in the last decade, but transactions were dominated by gold, and one deal in particular, the US$16.5bln acquisition of Newcrest by Newmont. In comparison, the 17 M&A transactions in copper and nickel recorded by S&P totalled less than US$5.3bln.

Smaller, more specialist transactions within the CRMs industry are likely, such as the 'merger of equals' between lithium producers Allkem and Livent worth US$10.6bln at the time of announcement in May 2023 (Arcadium Lithium 2023) and the recently announced (but subsequently withdrawn) non-binding agreement for US-based Albemarle to buy Australia's Liontown Resources (which started spodumene concentrate production from its Kathleen Valley project, Western Australia, in July 2024 (Liontown 2024c)) in a US$4.3bln deal (Albemarle 2023a & b). It is interesting to note the March 2024 announcements from Albemarle, upsizing its depository share offering from US$1.75bln to US$2.0bln, equivalent to US$1.94bln after deducting the underwriting discount and offering expenses (Albemarle 2024c). The underwriters exercised an option to purchase a further US$300mln (also upsized, from US$262.5mln). No doubt these funds may be used for acquisitions given that the recent collapse in lithium pricing makes the pricing of potential targets a lot more attractive. As a footnote, in July 2024, Liontown announced that LG Energy Solution would invest US$250mln in the company via convertible notes and LG's offtake agreement with Liontown was extended from 5 to 15 years (Liontown 2024b).

One obvious point to make, however, is that while an acquisition may enhance a particular corporate portfolio, it does nothing to promote the required increase in the world's CRMs production base if we wish to achieve Net Zero.

Collaboration required

The one key word that is necessary to link all of the themes that we have touched on is collaboration, without which it will be exceedingly difficult to secure the quantity of CRMs that we need not only for combating Climate Change and achieving Net Zero, but also for satisfying existing requirements and for the commercial development of other technological advances. It is therefore pleasing to see that while so many influencers (politicians, NGOs, financiers, industrialists and the wider public) remain ignorant of the requirement and scale needed to fast-track critical raw material resource development to meet these demands, we are beginning to see growing awareness of the challenge.

In December 2023, the World Economic Forum, in collaboration with McKinsey & Co. (2023), published a White Paper called 'Securing Minerals for the Energy Transition' with a major focus on collaboration; 'Global collaboration can raise awareness and drive action to tackle the disparity in supply and demand of critical minerals. On the contrary, isolated efforts by governments, the private sector and non-profit organisations are unlikely to address the energy transition challenge. Collaboration is necessary to unify efforts, mitigate regional imbalances and ensure sufficient and equitable supply of critical minerals'. The White Paper goes on to say 'The key themes for global collaboration include facilitating policy dialogue, supporting investment mobilisation, accelerating innovation, evaluating gaps in existing ESG standards, and building capabilities across the value chain'. These are all themes that we endorse, and indeed have considered in this paper, and the one key initiative that we would add to those outlined by the World Economic Forum is the issue of ensuring that we have sufficient numbers of skilled workers and managers in the mining industry across the globe to put these noble ideals into action. Here, as with the other initiatives, time is not on our side – we need to act now.

Conclusion

While many people are aware of the impact of climate change, most are unaware that to achieve Net Zero, and to reduce concentrated supply dependence (in particular to wean the world off China's influence across the supply chain), a huge investment is needed to increase Critical Raw Materials supply. According to one estimate (Energy Transitions Commission 2023), up to US$1.7 trillion may be required between 2021 and 2050. Others also forecast significant investment requirements. The IEA (2024c) estimates that between US$590-790bln will be required for copper, nickel and lithium if we are to meet its Announced Pledges Scenario emission target, while UNCTAD (2024) forecasts that between 2022 and 2030 US$360-450bln will be required to increase copper, nickel, lithium and cobalt capacity. Most people are totally unaware that to meet our 'green' targets we need to substantially increase production of CRMs – an electric car uses over six times the 'green' metals and minerals of a conventional petrol/diesel vehicle.

There is no guarantee that mineral exploration will lead to discovery, and one estimate suggests that the average cost per discovery has risen four-fold in the last two decades to US$240mln in the Western World, leading to direct financial challenges for junior exploration companies who are responsible for 90% of all recent discoveries (Schodde 2023). And once a discovery is made, it can take several years – often decades – for a mine to enter production. This needs to be reduced drastically.

If we are to satisfy the latent demand for CRMs we need to allow the mining industry to find and develop mineral deposits more quickly. The uncomfortable truth is that actual consumption rather than latent demand can only grow (once inventories have been fully utilised) at the rate of growth of supply. We expect the metals and mining industry to continue to push technological advances in exploration, mining, processing and urban mining, as well as considering the potential of contentious emerging frontiers (accessibility to land resulting from ice melt, phytomining, deep-sea mining, space mining).

But other stakeholders also need to play their part. If we wish to meet environmental targets and reduce supply dependence on certain countries then we, the citizens and politicians of the world, need to assist and not hinder mineral development. This means simplifying (not removing) planning, environmental, taxation and ownership criteria via better collaboration amongst all stakeholders, and we need a consistent approach so companies are not always trying to second-guess potential changes in taxes and royalty rates, or local ownership requirements. We need to see better provision of finance, in particular for junior exploration companies who play such a huge role in the discovery process; by definition junior explorers suffer from cash burn. Governments can do a lot more to stimulate the discovery and development of CRMs by providing or assisting with finance and ensuring that we have sympathetic policies that listen to all stakeholders, but do not produce permanent road-blocks to mineral project development.

For its part, the mining industry needs to sell itself better to the world's citizens; to promote itself as part of the solution and not part of the problem. Mining companies must uphold the highest ESG standards (walk-the-walk not talk-the-talk) and the industry must demonstrate its own 'green' credentials. There have been huge advances by the largest mining companies here, for instance in the development, with their industrial partners, towards all-electric mining fleets. Further technological advances will allow minerals and ores that are uneconomic or barely economic to be developed, and urban mining technology will increasingly allow CRMs to be recovered, for example from EV batteries and motors. The shortage of skilled labour and management and the need to promote a more gender-balanced workforce is a key long term challenge for the mining industry. There is no quick fix, but a better image, and acknowledgement that mining is part of the solution, not part of the problem, should help.

And above all, we need collaboration from all stakeholders if we are to meet our environmental targets and supply chain issues.

Table 8 – Automaker and mining company CRMs deals up to end 2023

Car co.	Mining company	Announced	Metal	Transaction	Country	Deal detail
BMW	Rio Tinto	21-Feb-23	Aluminium	MoU	Canada	Provide responsibly-sourced aluminium to BMW's S. Carolina plant from 2024
BMW	Jetti Resources	01-Dec-22	Copper	Equity investment	USA	Undisclosed investment in company advancing new copper extraction technology
BMW	European Li	05-Aug-22	Lithium	Non-binding MoU	Austria	US$15mln pre-payment if binding contract agreed
BMW	Mangrove Li	17-May-22	Lithium	Equity investment	Canada	Participated in US$25mln financing for lithium refining technology
BMW	Lilac Solutions	06-Oct-21	Lithium	Equity investment	USA	Participated in US$150mln financing for lithium brine extraction technology
BMW	Livent	18-Feb-21	Lithium	Off-take	Argentina	€285M supply agreement for lithium hydroxide 2022-2028
BMW	Ganfeng	17-Dec-19	Lithium	Off-take	Australia	€540M lithium hydroxide 2020-2024
BMW	Glencore	Apr-19	Cobalt	Off-take	Australia	No details
BMW	Managem	Jan-19	Cobalt	Off-take	Morocco	€100mln cobalt supply 2020-2025
Ford	Albemarle	May-23	Lithium	Off-take	Global	Supply >100,000t battery-grade lithium hydroxide; 5-year deal between 2026-2030
Ford	Compass Mins.	22-May-23	Lithium	Binding MoU	USA	5-year agreement to supply up to 4,400tpa LCE initially from 2025 start-up, rising to 14,000tpa LCE from brine production in Utah
Ford	PT Vale/ Huayou	30-Mar-23	Nickel	3-way investment	Indonesia	Processing plant producing 120,000tpa mixed hydroxide precipitate; uptake rights for 84,000tpa MHP nickel intermediate product
Ford	Ioneer	21-Jul-22	Lithium	Binding off-take	USA	7,000tpa lithium carbonate 2025-2030
Ford	Syrah Res./ SK On	22-Jul-22	Graphite	Non-binding MoU	USA	Considering supply of natural graphite active anode material from Syrah's Vidalia, Louisiana, facility
Ford	BHP	21-Jul-22	Nickel	Non-binding MoU	Australia	Nickel West to supply nickel from 2025
Ford	Rio Tinto	21-Jul-22	Various	Non-binding MoU	Various	Considering becoming foundation customer for Rincon (lithium, Argentina); low-carbon aluminium and copper
Ford	Vale	02-Jul-22	Various	Non-binding MoU	Canada	Exploring opportunities across the EV value chain
Ford	Liontown Res.	29-Jun-22	Lithium	Binding off-take	Australia	Up to 150,000dmln tpa spodumene concentrate from 2024 for 5 years
Ford	Lake Res.	11-Apr-22	Lithium	MoU	Argentina	Supply agreement for 25,000tpa lithium
GM	Element 25	26-Jun-23	Manganese	Loan & off-take	USA	Loan of US$85mln to Element 25 to part fund first manganese sulphate facility in the USA (2025 start-up); to supply 32,500tpa to GM
GM	EnergyX	11-Apr-23	Lithium	Funding/ tech dev.	USA	Leading US$50mln Series N financing round and strategic agreement to develop DLE technology
GM	Li Americas	31-Jan-23	Lithium	Equity & offtake	USA	US$650mln investment; exclusivity to Phase 1 output (40,000tpa Li2CO3) from Thacker Pass. 10-year deal; 5-year extension option
GM	Vale	17-Nov-22	Nickel	Off-take	Canada	Long-term supply agreement for battery-grade nickel sulphate (up to 25,000tpa contained nickel
GM	Queensland Pac.	11-Oct-22	Nickel/ cobalt	Equity & off-take	Australia	US$69mln equity investment to assist development of the Townsville Energy Chemicals Hub
GM	Livent	26-Jul-22	Lithium	Off-take/ pre-pay.	Unspec.	6-year lithium hydroxide deal starting 2025; US$198mln pre-payment made in 2022
GM	Glencore	12-Apr-22	Cobalt	Off-take	Australia	Multi-year supply agreement for cobalt from the Murrin Murrin mine
GM	MP Materials	09-Dec-21	Rare Earths	Strategic collab.	USA	Strategic collaboration to create a fully integrated US supply chain for Rare Earth magnets, starting 2023
GM	GE Renewable	06-Oct-21	Rare Earths	Non-bind. MoU	USA	MoU to evaluate opportunities to improve supplies of Rare Earths materials and magnets, copper and electrical steel
GM	Controlled Therm.	02-Jul-21	Lithium	Equity	USA	Multi-million dollar investment to aid development of Hell's Kitchen project in California
Hyundai	Korea Zinc	30-Aug-23	Nickel	MoU	Global	Collaboration to source nickel raw material, processed nickel and other battery materials, and consider battery recycling
Hyundai	PT Adaro	13-Nov-22	Aluminium	Off-take	Indonesia	Agreement to supply an unspecified amount (but in the range of 50-100,000tpa) of low-carbon aluminium

Hyundai	Arafura Res.	07-Nov-22	Rare Earths	Off-take	Australia	Binding agreement to supply 1,500tpa Nd Pr oxide (or metal equivalent)
M.-Benz	Rock Tech Li	20-Oct-22	Lithium	Off-take	Germany	Definitive 5-year agreement for an average of 10,000tpa battery-grade lithium hydroxide preceded by a qualification period in 2026
M.-Benz	Canadian govt.	23-Aug-22	Various	MoU	Canada	Agreement to cooperate across all stages of the automotive value chain, including sourcing raw materials
Renault	Terrafame	Dec-22	Nickel	Off-take	Finland	Multi-year agreement for low-carbon nickel sulphate
Renault	Managem	01-Jun-22	Cobalt	Off-take	Morocco	Agreement to supply 5,000tpa low-carbon cobalt sulphate for 7 years starting 2025
Renault	Vulcan Energy	22-Nov-21	Lithium	Off-take	Germany	Binding agreement to supply 26,000-32,000tpa of battery-grade lithium hydroxide for 6 years starting 2026
Stellantis	Controlled Therm.	17-Aug-23	Lithium	Invest./ off-take	USA	US$100mln investment to advance Hell's Kitchen; offtake increased from 25,000tpa (June 22) to 65,000tpa of lithium hydroxide
Stellantis	NioCorp	06-Jul-23	Rare Earths	Off-take	USA	Off-take agreement for Rare Earths from the Elk Creek, Nebraska, project subject to economic viability of project
Stellantis	Kuniko	30-Jun-23	Nickel/ cobalt	Equity & off-take	Norway	€5mln equity deal (19.99% of Kuniko); binding off-take for 35% of future production of battery-grade Ni and Co sulphates for 9 years
Stellantis	Alliance Ni	28-Apr-23	Nickel/ cobalt	Equity & off-take	Australia	€9.2mln equity investment (11.5% of company); binding offtake for 170,000t and 12,000t of Ni and Co sulphates over 5-year period
Stellantis	McEwen Cu	27-Feb-23	Copper	Equity	Argentina	US$155mln investment for 14.2% of McEwen Copper; Los Azules mine to produce 100,000tpa copper cathode for 33 years from 2027
Stellantis	Terrafame	18-Jan-23	Nickel	Off-take	Finland	Off-take agreement for low-carbon nickel sulphate starting in 2025 for 5 years
Stellantis	Element 25	09-Jan-23	Manganese	Off-take	Australia	Binding agreement to deliver 45,000t total battery-grade high purity manganese sulphate monohydrate over 5 years starting 2026
Stellantis	GME Res.	09-Oct-22	Nickel/ cobalt	MoU	Australia	Non-binding agreement to supply nickel and cobalt sulphates from the NiWest project
Stellantis	Vulcan Energy	24-Jun-22	Lithium	Equity & off-take	Germany	€50mln equity investment and extension of original offtake agreement to 10 years
Stellantis	Vulcan Energy	29-Nov-21	Lithium	Off-take	Germany	Binding agreement to supply 81,000-99,000 battery-grade lithium hydroxide over 5 years starting 2026
Tesla	Magnus	21-Feb-23	Graphite	Off-take	USA	Binding offtake for minimum 17,500tpa of Anode Active Materials (option to go to 35,000tpa) from Feb. 2025 for minimum 3 years
Tesla	Piedmont Li	03-Jan-23	Lithium	Off-take	USA	Revised binding agreement for 125,000t spodumene conc. from H2 23 to end 2025; 2nd 3-yr option. Original deal 28 Sept. 2020
Tesla	Core Li	29-Aug-22	Lithium	Off-take	Australia	Binding agreement for up to 110,000t of spodumene concentrate. Termsheet not completed by 26 Oct. 22 deadline. Deal lapsed
Tesla	Huayou	31-Jul-22	Nickel/ cobalt	Off-take	China	Nickel and cobalt sulphates for delivery July 2022 to December 2025. Long-term supplier
Tesla	CNGR	31-Jul-22	Nickel/ cobalt	Off-take	China	Nickel and cobalt sulphates for delivery January 2023 to December 2025. Long-term supplier
Tesla	Liontown Res.	06-Jun-22	Lithium	Off-take	Australia	5-year spodumene concentrate agreement, starting 2024. 100,000t in Year 1, 150,000tpa in subsequent years
Tesla	Vale	06-May-22	Nickel	Off-take	Canada	Long-term supply agreement
Tesla	Syrah Res.	23-Dec-21	Graphite	Off-take	USA	4-year agreement to supply 8,000tpa Active Anode Material, subject to certain conditions
Tesla	Ganfeng	01-Nov-21	Lithium	Off-take	China	3-year deal from 2022 for battery-grade lithium. Long-term supplier
Tesla	Yahua	29-Dec-20	Lithium	Off-take	China	5-year battery-grade lithium hydroxide agreement
Tesla	Wesfarmers	May-18	Lithium	Off-take	Australia	3-year supply agreement for lithium hydroxide with 2 further 3-year options
Tesla	Pure Energy Mins.	16-Sep-15	Lithium	Off-take	USA	5-year offtake agreement subject to proof of economic viability of Clayton Valley, Nevada, brine project
Tesla	Prony Res.	Long-term	Nickel	Off-take	New Caledonia	Existing long-term offtake supplier

Tesla	BHP	Long-term	Nickel	Off-take	Australia	Existing long-term offtake supplier
Tesla	Glencore	Long-term	Nickel/ cobalt	Off-take	Australia	Existing long-term offtake supplier
Tesla	Livent	Long-term	Nickel/ cobalt	Off-take	Unspecified	Existing long-term offtake supplier
Tesla	Albemarle	Long-term	Lithium	Off-take	Unspecified	Existing long-term offtake supplier
Toyota	Ioneer	01-Aug-22	Lithium	Off-take	USA	Binding offtake agreement for Prime Planet Energy & Solutions (Toyota/Panasonic JV) to take 4,000tpa lithium carbonate for 5 years
Toyota	BHP	04-Oct-21	Nickel	MoU	Australia	Agreement with Prime Planet Energy & Solutions and Toyota Tsusho to supply NiSO4 as part of a greater collaborative alliance
VW	Canadian govt.	23-Aug-22	Various	MoU	Canada	Agreement to cooperate across all stages of the automotive value chain, including sourcing raw materials
VW	Huayou/ Tsingshan	21-Mar-22	Nickel/ cobalt	MoU	Indonesia	3-way JV to procure up to 120,000tpa nickel and 15,000tpa cobalt for Volkswagen
VW	Vulcan Energy	12-Aug-21	Lithium	Off-take	Germany	Binding lithium hydroxide supply agreement for 5 years starting 2026
VW	Umicore	12-Aug-21	Various	Strategic partner.	Unspecified	JV to supply cathode materials starting 2025
VW	Ganfeng	08-Apr-19	Lithium	Off-take	China	10-year offtake agreement

Source: automaker and mining company websites

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