THE SUPERPOWER TRANSFORMATION

Making Australia's zero-carbon future

EDITED BY

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THE NET-ZERO OPPORTUNITY FOR AUSTRALIAN MINERALS

Mike Sandiford

The net-zero carbon economy requires decarbonisation of all sectors of the economy, especially those which have traditionally been served by fossil fuels, such as electricity, transport and mineral processing. That translates to a huge increase in demand for magnets and batteries, and the many other technologies that provide the essential building blocks that will allow for the 'electrification of nearly everything'. In turn, that creates a huge increase in demand for many relatively scarce metals such as lithium, cobalt, neodymium, praseodymium and vanadium, as well as the more abundant metals such as iron, aluminium, copper and nickel that are necessary for the structural framework and much of the communication and transport infrastructure that has underpinned the development of the modern global economy. For rapid decarbonisation, extraordinary increases in supply of the critical energy transition metals will be necessary, both in terms of rates of growth and in magnitude.

For example, electric cars contain up to five times as much of these rarer, energy transition metals as conventional cars do.[1] Demand for lithium, nickel, manganese and a raft of scarcer metals such as cobalt, vanadium and some of the rare earth elements (REE) such as neodymium, will rise many-fold in a net-zero-carbon world. The International Energy Agency estimates in its net-zero pathway scenario that the total market for copper, cobalt, manganese and various rare earth elements will need to grow by almost 700 per cent between 2020 and 2030.[2]

But it is not just the new rare metals for which demand will increase. As the most copper- and steel-intensive form of energy production, and as a mainstay of a fully renewable energy system, wind power will drive high demand not only for the REEs but also for traditional industrial metals steel and copper. Each new megawatt of wind power capacity absorbs between 120 and 180 tonnes of steel and between 5 and 14 tonnes of copper. The expected deployment of 650 gigawatts of new onshore wind capacity and 130 gigawatts of offshore wind capacity by 2028 will see demand for copper rise to 5.5 million tonnes per annum,[3] an increase equivalent to about 25 per cent of current global production.

Deep decarbonisation raises a suite of urgent questions[4] such as 'where and how are we going to source them?', 'what will be the impacts of price shocks that will accompany inevitable demand-supply imbalance', 'what geopolitical consequences will flow from the winners and losers on the new chessboard of rare metal supply? and 'what are the economic, social, and environmental costs for securing supply chains?'.

A zero-carbon economy will afford significant economic and strategic advantage to countries with significant geological endowments of critical metallic minerals, especially if they have globally competitive

Table 3.1 US Geological Survey (USGS) list of critical elements, ordered by crustal scarcity (relative to iron), with Australian production and reserves by global rank and main uses. Light grey signifies current Australian production. White signifies no known significant Australian reserve. Dark grey signifies known Australian reserves with no current or only very limited production (for example, Australia has vast silicon potential but only very limited current production at SIMOCA's facility at Kemerton in Western Australia) but potential for globally significant future production.

USGS proposed list of critical elements; Australian production and reserve rankings

Element		Scarcity	Prod.	Res.	Use
Silicon		0.2	–	–	alloys, semi–conductors
Aluminum		0.684	1st	1st	almost all sectors of the economy
Iron		1	1st	1st	steel
Magnesium		2.42	10th	4th	alloy, for reducing metals
Titanium		9.96	3rd	2nd	white pigment or metal alloys
Hydrogen		40.2	–	–	energy carrier, fertiliser
Manganese		59.3	2nd	2nd	steelmaking, batteries
Zirconium		341	1st	1st	high–temperature ceramics, corrosion–resistant alloys.
Vanadium		469	–	3rd	alloying agent for iron, steel, batteries, batteries
Chromium		552	–	–	stainless steel, other alloys
Rubidium		626	–	–	research, development electronics
Nickel		670	6th	2nd	stainless steel, superalloys, rechargeable batteries
Zinc		804	2nd	1st	metallurgy to produce galvanized steel
Cerium*	REE	847	4th	6th	catalytic converters, ceramics, glass, metallurgy, polishing compounds
Copper		938	6th	3rd	almost all sectors of the economy
Neodymium*	REE	1,360	4th	6th	permanent magnets, rubber catalysts, medical and industrial lasers
Yttrium		1,710	–	–	ceramic, catalysts, lasers, metallurgy, phosphors
Cobalt		2,250	3rd	2nd	rechargeable batteries, superalloys
Scandium		2,560	–	–	alloys, ceramics, fuel cells
Lithium		2,820	1st	2nd	rechargeable batteries
Niobium		2,820	–	–	steel, superalloys
Gallium		2,960	–	–	integrated circuits, optical devices like LEDs
Praseodymium*	REE	6,120	4th	6th	permanent magnets, batteries, aerospace alloys, ceramics, colorants
Samarium*	REE	7,990	4th	6th	permanent magnets, as an absorber nuclear reactors, in cancer treatments
Gadolinium*	REE	9,080	4th	6th	medical imaging, permanent magnets, steelmaking
Dysprosium*	REE	10,800	4th	6th	permanent magnets, datstorage devices, lasers
Erbium*	REE	16,100	4th	6th	fiber optics, optical amplifiers, lasers, glass colorants
Ytterbium*	REE	17,600	4th	6th	catalysts, scintillometers, lasers, metallurgy
Cesium		18,800	–	–	research, development
Hafnium		18,800	–	–	nuclear control rods, alloys, high–temperature ceramics
Beryllium		20,100	–	–	alloying agent aerospace, defense industries
Tin		24,500	8th	3rd	protective coatings, alloys for steel
Europium*	REE	28,200	4th	6th	phosphors, nuclear control rods
Tantalum#		28,200	7th	1st	electronic components, mostly capacitors, superalloys
Arsenic		31,300	–	–	semi–conductors
Germanium		37,500	–	–	fiber optics, night vision applications
Holmium*	REE	43,300	4th	6th	permanent magnets, nuclear control rods, lasers
Terbium*	REE	46,900	4th	6th	permanent magnets, fiber optics, lasers, solid–state devices
Lutetium*	REE	70,400	4th	6th	scintillators for medical imaging, electronics, some cancer therapies
Thulium*	REE	108,000	4th	6th	metal alloys, lasers
Indium		225,000	–	–	liquid crystal display screens
Antimony		282,000	6th	5th	lead–acid batteries, flame retardants
Palladium		3,750,000	–	–	catalytic converters, as catalyst agent
Bismuth		6,620,000	–	–	medical, atomic research
Platinum		11,300,000	–	–	catalytic converters
Iridium		56,300,000	–	–	coating of anodes for electrochemical processes, as chemical catalyst
Rhodium		56,300,000	–	–	catalytic converters, electrical components, as catalyst
Ruthenium		56,300,000	–	–	catalysts, as well as electrical contacts, chip resistors computers
Tellurium		56,300,000	–	–	solar cells, thermoelectric devices, as alloying additive

renewable energy resources for processing minerals into metals. For countries with both, there will be distinctive and immense economic opportunity in developing zero-emission mineral supply chains that include both mining and metal processing. Australia is one such lucky country, and it seems the luckiest of all. Peter Farley estimates that domestic processing of iron ore into green iron could increase total value of Australian exports by $70–120 billion each year, depending on plausible assumptions about the costs of hydrogen production and electrolysers, as well as premiums and carbon prices.[5] That amounts to 15 to 25 per cent of 2021 total exports value, or 1.2 to 2.1 multiple on the 2021 rural goods export value. Added to the imperatives dictated by climate change, the production and refining of these scarce metals is increasingly associated with strategic geopolitical supply risks.

While future demand for the energy transition elements will rise rapidly, the specific demand for individual metals will depend on technological developments that have yet to play out. Manganese and vanadium are essential ingredients for contenders for large-scale 'flow' batteries, as is iron. Which technology wins out may turn on supply security as much as pricing or environmental risk.

Many of the scarcer metals essential to the energy transition are collectively referred as 'critical metals' or 'critical minerals'. The term 'critical' refers to both their use in essential technologies and their exposure to geopolitical threats posed by geographically limited supply chains. The United States Geological Survey (USGS) lists fifty elements in its 2021 critical mineral list, of which only twenty are critical to energy technologies.[6] The REEs are a particular concern because more than 80 per cent of the global supply is currently sourced from China.

Global supply chains for critical minerals concerns also include environmental, social, ethical and pricing risks. Mineral processing can incur severe environmental risks. In countries with governments that are prepared to tolerate higher levels of environmental risk, or apply lax regulation, refined mineral product can be supplied at a significant cost advantage. Rare earth supply is largely controlled by China, not just because of rich primary resource endowments, but also because of tolerance of refining processes that are reportedly already risking significant environmental damage.[7] Around 60 per cent of the global supply of cobalt is sourced from poorly regulated artisanal mining in the Democratic Republic of Congo, where the safety of miners is largely unregulated.[8]

Recently, the term 'critical' has gained currency in reference to the essential role of these rare metals in the energy transition. However, as noted earlier, the energy transition is equally dependent on the more abundant metals such as copper, manganese and iron. It is better to use a more inclusive term to summarise both the challenge and the opportunity. Here I use 'energy transition metals'.[9]

A central concern for energy transition metals is whether supply can match demand derived from achievement of net-zero carbon consistent with climate objectives such as limiting warming to 1.5°C. The International Energy Agency (IEA)'s net-zero pathway requires year-on-year growth of about 50 per cent for key metals over the next decade. This is against a backdrop where primary discovery rates for large metal deposits have been declining for several decades. The search space for mineral explorers is becoming riskier and more expensive.

There are concerns about the scale of future recoverable resources for conventional metallic minerals such as copper, for which the fundamental geochemistry is now well understood. The fraction of the stock of recoverable copper already in use, or in wastes from which it will probably never be recovered, was estimated to be already at ~26 per cent as long ago as 2005.[10] While such estimates are highly uncertain, it points to the challenge in any massive ramp-up in future demand as implicit in net zero carbon. How do we ensure we find enough of the stuff to supply demand? The question of peak supply for metals has been a recurring theme for resource economists, for over a century in the case of copper.[11]

Many of the metals that are important for the energy transition are scarce and have few or no primary geochemical mineral enrichments. Such metals are referred to as 'companion' metals and are usually sourced using secondary recovery processes from ores that are mined for primary metals such as copper. For many companion metals, there are likely to be substantial stocks in existing mining wastes, such as smelter slags and tailings. For some companion metals, such as indium and scandium, the lack of fundamental geochemical knowledge about their distribution means assessments of resource availability are extremely uncertain.

Of great importance for the energy transition is the likely severe price impacts of inevitable supply-demand imbalance. If supply cannot meet demand at any time, then price of the scarce material will rise sharply, rationing limited supplies through the price mechanism. Some manufactures that depend on the input will curtail production, reducing demand and forcing price to lower levels. The associated price and supply instability can reduce investment both in the mineral supply and the minerals-using industries. Extreme volatility will slow movement along the decarbonisation pathway.[12] The International Monetary Fund (IMF) estimated that real prices of nickel, cobalt and lithium could rise several hundred per cent from 2020 levels on the IEA's net-zero emissions scenario,[13] with the total value of the metals production potentially increasing more than fourfold. In such a scenario, total value of these metals along with copper is anticipated to rival the 'value of oil production in a net-zero emissions scenario', potentially yielding extraordinary windfalls for producing and exporting nations. Of particular relevance for Australia is the IEA anticipation that, on its net-zero pathway, the total value of critical metals will exceed that of the global coal trade as early as 2030. Pricing concerns are already being realised, with scarcity pricing currently delivering significant windfall gains for resource producing countries. Across 2021, lithium, cobalt and neodymium prices rose by 525 per cent, 95 per cent and 75 per cent, respectively. Lithium prices doubled again in the first three months of 2022.

Even in very optimistic outlooks, with all new and proposed resource projects currently in the pipeline eventuating, raw material supply will likely limit future battery demand. Some forecasts have lithium carbonate supply falling short of currently indicated production by more than 300,000 tonnes by 2030,[14] equivalent in magnitude to the global production in 2020. Nickel sulphate may be in deficit by nearly 400,000 tonnes, cobalt by over 75,000 tonnes and flake graphite by nearly 2 million tonnes. If such supply constraints were to apply, they would severely limit battery production, possibly to no more than about 1 TWh per annum until well after 2025.

Supply concerns are by no means new. Long ago, noted resource geologist Brian Skinner raised concerns about the mineralogical barriers that may limit resource availability, especially for the scarcer 'companion' metals.[15] However, historically the supply of raw commodities has quickly followed rising demand and prices, keeping resource prices in check. This phenomenon was most famously evidenced in the Erhlich–Simon wager.[16] In 1980, Julian Simon challenged Paul Ehrlich to choose a basket of raw materials and a date more than a year away, wagering the inflation-adjusted prices would decrease, not increase. Ehrlich chose copper, chromium, nickel, tin and tungsten, and a ten-year period. When the wager settled in 1990, inflation adjusted prices for all commodities had decreased despite Ehrlich's anticipated demand pressures driven by rising population and an expected decline in natural resource inventories. The 'cornucopian' Simon won. Simon has been extremely critical of the notion of 'peak resources'.[17] For example, even though the idea of 'peak copper' has been persistent for almost

100 years, Simon points out that at least up until the late 1990s reserve growth outpaced demand, as evidenced by falling long-run price of copper. Simon reasons that rising prices provide impetus to seek technological improvements that when realised inevitably open substantial new resource opportunities. In recent times, this is most evident in the use of horizontal drilling and fracking in unconventional oil and gas plays that have largely put paid to the 'peak oil' concerns that were prevalent twenty years ago.

The transition to net-zero emissions will provide both challenges and opportunities for the Australian mining sector. As a resource-rich country, unique in its continental scale and geological diversity, Australia has advantages in its natural mineral resource endowments. Not only can Australia be a leading supplier for many of the raw commodities essential for the energy transition, but with its high-quality renewable resources it has natural advantage in a net-zero world as a potential home for energy-intensive mineral processing. Realising this potential will require an intensive search for new resources, and innovation in much less carbon-intensive approaches to mineral processing. This is set against a backdrop of a higher education system which is disinvesting in many of the most relevant disciplines, such as the geosciences. For several of the most important relevant disciplines, such as geophysics and metallurgy, the collapse in university training and research is especially alarming, with current trajectories headed for their extinction, just as the industry demand for such specialist training rises to unprecedented levels. Historically, Australia has been robust in delivering skilled workforces in fields such as geosciences and metallurgy. This can no longer be guaranteed.

The potential for a vastly expanded mining sector, inclusive of mineral processing, raises important issues for policy-makers across the spectrum of mineral resources development, with the need to balance environmental, social, security and economic concerns. How capital is distributed between resource recovery and mineral processing will require careful consideration, and appropriate policy development. The opportunity for mining and processing of critical minerals in Australia is geographically diverse and, managed appropriately, could provide a boon for regional and rural development.

Dig it up and ship it out

The Reserve Bank of Australia estimates mining makes up about 12 per cent of Australian industry output, and 60 per cent of export share.[18] Current production is dominated by iron ore. Annual Australian iron-ore exports now stand at over 900 million tonnes, accounting for about 36 per cent of total global demand and 56 per cent of global exports.[19] Australia is also the leading global supplier of bauxite (for aluminium), lithium and

Table 3.2 USGS production statistics for 2021.

Commodity	Australian production	Global production (%)	Global rank	Leading producer country, %
Lithium	40,000	49	1	Australia, 49
Iron ore	900,000,000	38	1	Australia, 38
Bauxite	110,000,000	30	1	Australia, 30
Manganese	3,300,000	18	2	South Africa, 28
Zinc	1,400,000	12	2	China, 35
Lead	480,000	11	2	China, 43
Gold	320	10	2	China, 12
Cobalt	5700	4	3	Congo, 68
Rare earths	17,000	7	4	China, 58
Nickel	170,000	7	6	Indonesia, 30
Copper	870,000	4	6	Chile, 28

Note: production units – metric tonnes.

rutile (for titanium); second in manganese, gold, zircon and lead; and third in uranium and copper. Australia also has significant reserves of rare earth elements, silicon, magnesium and vanadium, and prospects for much rarer critical metals such as indium and gallium.

The changing role of minerals in the Australian economy is highlighted by the monetary value of exported goods – or so-called goods credits (Table 3.2). Fifty years ago, metallic minerals accounted around 24 per cent of total Australian goods credits, compared with rural goods at 50 per cent. Currently the metallic mineral sector makes up around 44 per cent of the total, with rural goods at 12 per cent. Fossil fuels including coal and liquified natural gas (LNG) make up 25 per cent.

Table 3.3 USGS commodity reserve statistics.

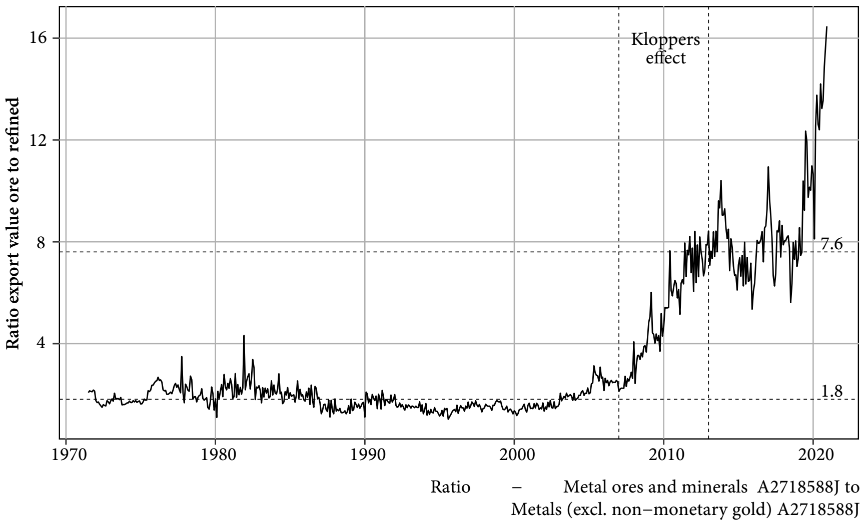
Commodity	Australian reserves	Global reserve (%)	Global rank	Leading reserve country, %
Lead	36,000,000	41	1	Australia, 41
Zinc	25,000,000	37	1	Australia, 37
Iron ore	50,000,000,000	28	1	Australia, 28
Gold	10,000	19	1	Australia, 19
Bauxite	5,100,000,000	17	1	Australia, 17
Lithium	4,700,000	22	2	Chile, 44
Manganese	270,000,000	21	2	South Africa, 40
Nickel	20,000,000	21	2	Indonesia, 22
Cobalt	1,400,000	20	2	Congo, 20
Vanadium	4,000,000	18	3	China, 43
Copper	88,000,000	10	3	Chile, 23
Rare earths	4,100,000	3	6	China, 37

Note: Reserve units – metric tonnes. Note that comparison of reserves, are uncertain due to the different methodologies employed across countries. Australian reserve estimates are JORC compliant.

Since the turn of this century, there has been a dramatic rise of total mineral goods exports. This comprises both raw ore exports such as iron ore and refined products such as manganese metal, alumina and aluminium. To a large extent, the growth has been driven by burgeoning Chinese demand and is almost entirely attributable to primary ore. In contrast, there has been no significant growth in the value of refined metal exports.

Prior to 2000, the value of mineral ores export credits sat at about 1.8 times the refined metal production. This ratio is now at around fifteen and reflects the progressive shift in capital allocation in the resource sector almost exclusively to mine development, at the expense of mineral processing. The Australian resource sector is now essentially focused on the digging up of raw product, as perhaps exemplified by the industry 'dig it up and ship it out' mantra espoused most prominently by former BHP CEO Marius Kloppers.[20]

Figure 3.1 Ratio of value of exported Australian ore to exported Australian processed metals.



Source: Data sourced from the Australian Bureau of Statistics.

Table 3.4 Goods export credits by sector as percentage of total.

	Rural	Fuels	Minerals	Other
1971–73	50	6	24	21
1999–2001	24	20	21	35
2019–21	12	25	44	19

Source: Data sourced from ABS 5368.0, TABLE 5[21], averaged over last two years.

Note: Fossiwl fuels aggregates 'Coal, coke and briquettes' and 'Other mineral fuels'. Minerals and metals aggregates 'Metal ores and minerals' and 'Metals (excl. non-monetary gold)'.

The 'dig it up and ship it out' approach has several important consequences. One is the relocation offshore of processing emissions, which are therefore not counted against Australia's national emissions accounts. This is significant. Scope 3 emissions from offshore processing to metallic iron of Australian iron ore exports in 2020 are more than 900 MT-CO_2e, or about 180 per cent of Australian domestic emissions.[22]

Outlook for energy transition metal resources

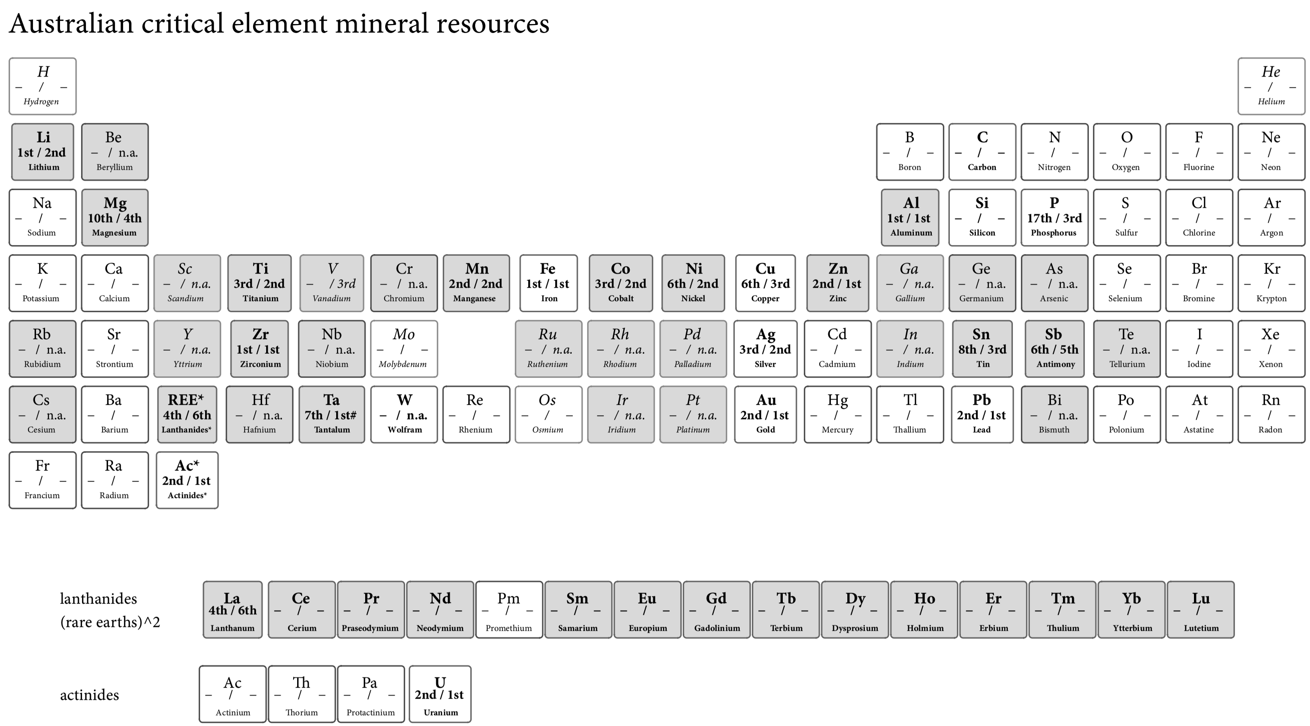
As a leading resource producer for a range of minerals, Australia has over 300 operating mines producing twenty-six mineral commodities.[23] In terms of tonnage, iron and aluminium ores are the largest primary metal ores mined in Australia. While not typically considered as 'critical minerals', they are critically important to the energy transition and will remain central to Australian mineral resource production. Here I explore the current status and outlook for recovery of several of the other main energy transition metals.

The energy transition metals represent a geochemically diverse array of metals, with prospective resources distributed widely across Australia. There are significant prospects in all states. The most prospective regions are in the traditional resource-rich metal provinces of the Yilgarn and Pilbara of Western Australia, the Gawler and Curnamona in South Australia, Mount Isa in Queensland, and Broken Hill in New South Wales. In many instances the resource inventories for the critical minerals transition metals are poorly understood and there is much uncertainty. Resources include primary geological endowments, such as the lithium-bearing spodumene pegmatites in Western Australia, secondary enrichments where deep weathering has concentrated metals in the near-surface laterites, such as applies to many existing Australian iron, bauxite and manganese deposits, which also host cobalt and scandium. In addition, there are significant resource endowments of metals such as cobalt in existing mine wastes, including smelter slags and mine tailings.

Lithium is the emblematic 'energy transition metal', being the essential ingredient in the batteries that are currently in greatest demand. It is sourced globally from both hard rock mineral and brine mining. Brine mining is dominated by Bolivia and Peru, in the high Andes. The USGS reports total lithium 2020 production at 82,000 tonnes. The IEA's zero-carbon pathway anticipates lithium demand will grow thirty-fold to 2030 and more than 100-fold by 2050.

Australia is the leading lithium supplier, accounting for around 40 per cent of global supply. All Australian production comes from lithium-bearing pegmatites, with the principal ore-bearing mineral being spodumene. Current supply is from Western Australia. New mines are under active development in both Western Australia and the Northern Territory, which will see significant expansion of production in 2022. The lithium content of the Australian reserve (4,700,000 tonnes) had a value of approximately $500 billion at 2020 prices. Australia has no significant identified lithium brine resources.

The REEs comprise a group of the fifteen lanthanides, along with scandium and yttrium. The most critical REEs for the energy transition are neodymium, dysprosium, praseodymium and terbium. These



^1. Uranium rankings from World Nuclear Acssociaton – https://www.world–nuclear.org/information–library/nuclear–fuel–cycle/mining–of–uranium/world–uranium–mining–production.aspx
^2. USGS reports lanthanide production/reserve data as bulk rare earths, rather than by individual element
critical element reserve data not available for Australia (n.a.) or poorly known/unknown for other leading producing countries (#)

Figure 3.2. 'Periodic table' of Australian metal production and reserves by global rank. USGS listed critical metals in shaded grey. Australian metals production/reserves by global rank in bold. Australian significant reserves by global rank but no production in italic.

are essential ingredients in permanent magnets that are vital for wind turbines and electric vehicles. Rare earth production is dominated by China, with Australia responsible for about 7 per cent of global production. Two leading Australian rare earth miners have plans for the development of mineral processing facilities in Australia. Iluka has committed to building a refinery at Eneabba in Western Australia, with agreement on a risk-sharing arrangement with the Australian federal government, including through a non-recourse loan under the government's $2-billion Critical Minerals Facility, administered by Export Finance.[24] The Lynas Mt Weld mine in Western Australia is one of the world's premier rare earths deposits. Currently Lynas operates the world's largest single rare earth processing plant in Malaysia, and it has announced plans to build a $500-million refinery at Kalgoorlie.[25]

Manganese is used primarily as a steel additive, and increasingly for batteries. Australia is the second-largest ore producer at 18 per cent global production and 21 per cent global reserve, with the majority of ore sourced from Groote Eylandt in the Northern Territory. About 10 per cent of the ore is processed domestically in Tasmania, with the remaining 90 per cent (approximately) shipped overseas. The long-term outlook for manganese production is unclear, with the current South32 mining operations on Groote Eylandt set for closure before 2030.[26] Most Australian manganese prospects are secondary enrichments in ancient, deeply weathered zones above manganese-rich host rocks. Deeply weathered metal-rich laterites are relatively abundant across northern Australia, though manganese concentrations are typically sub-economic.

Global cobalt production is currently dominated by the Democratic Republic of Congo (around 73 per cent). Australia accounts for about 5 per cent. Due to its low concentration in ores, cobalt is typically mined as a companion metal as a byproduct of extraction of copper, nickel and arsenic.[27] At current prices the value of cobalt in Australian listed reserves is $114 billion. Given the significant historic production of copper in Australia, there is significant potential for cobalt in mine wastes, including smelter slag waste such as Mount Isa. Economic cobalt prospects are probable in nickel-bearing laterites.

Vanadium usually constitutes less than 2 per cent of the host rock. Because vanadium is typically recovered as a byproduct or co-product, demonstrated world resources of the element are not fully indicative of available supplies. At 60 per cent, China is the world's major supplier, followed by Russia (17 per cent) and South Africa (7 per cent). In 2019, global production was 73,000 tonnes. Australia has significant demonstrated vanadium reserves, with mines in development in Queensland and several deposits in Western Australia in pre-feasibility. The Queensland resource is hosted by the Toolebuc Formation, an oil shale in the Eromanga Basin outcropping extensively in the Julia Creek region, as well as near Barcaldine. The vanadium content of the indicative Australian reserve of about 4 million tonnes has a notional value of approximately $125 billion at 2020 prices. The Saint Elmo mine, which commenced construction in 2022, is initially forecast to produce up to 5000 tonnes of vanadium pentoxide per annum (approximately 2800 tonnes of vanadium).[28] The Vecco group has advanced plans for mining at Debella and plans to construct and operate the first vanadium battery electrolyte manufacturing plant in Australia. Australian Vanadium Limited has an advanced project near Geraldton in the mid-west of Western Australia. Both mines are located near world-class renewable energy resources, which will facilitate low-emission processing.

The future of Australian mineral resource processing

Currently, the carbon emissions embodied in processing Australian ore exceed 1 billion tonnes of CO_2-equivalent per annum, constituting many times Australia's own emissions. Almost all processing of Australian ore is now undertaken offshore. In a future zero-carbon world, global metal-refining capability will have to be totally rebuilt to address emissions intensity, energy supply cost changes and global supply chain issues. This will provide opportunity for countries such as Australia which have natural comparative advantage based on cheap renewable energy generation.

In addition to the natural advantages afforded by cheap renewable energy production and natural metal endowments, emerging geopolitical risks in global supply chains are one of the key defining issues for supply of many of the critical energy transition metals. There are therefore security reasons for developing an indigenous processing capacity. Battery supply chains are atypical in that they require much higher-purity metal inputs than for other uses. Consequently, there is need for very careful attention to the specific geochemistry of the primary ores and their metallurgy, something for which Australia's diverse natural endowments should provide competitive advantage.

In terms of conventional metals, such as iron, the principal source of emissions relate to the use of coal as the source of both energy for smelting (mainly heating) and as the reductant for liberating the metal from the oxidised primary ore. Decarbonising the metal refining process will require new technology based on non-fossil sources of reduction and energy. In the future zero-carbon world, the reductant of choice will be green hydrogen, and for energy it will be the cheap renewables, solar and wind.

The key challenge for renewable energy sources for metal refining relates to the need for relatively constant thermal loads. Thermal processing is essential to most current metal refining and is inherently inflexible. This is most notorious for aluminium processing, which is often jokingly referred to as 'congealed electricity'. In the main Hall-Héroult process, alumina is reduced to liquid aluminium metal at temperatures of about 950°C in 'pots'. Producing a tonne of aluminium metal requires roughly the same amount of electricity as is used by an average home in a year.

Consequently, energy consumption typically accounts for almost half the cost of aluminium refining.

While thermal processing can be varied, there are limits to the extent. For conventional aluminum processing those limits are likely to be in the range 10 to 20 per cent of total energy demand. For renewable energy supply, this adds substantially to the cost. New technologies such as EnPOT allow for up to 30 per cent intra-day variability in energy demand, allowing more scope for smelters to arbitrage energy market opportunities. Providing load 24/7 across all seasons within a limited range of variability will require a mix of strategies. In order to secure high returns on mineral processing capital investments, there will need to be significant energy storage, in chemical batteries, gravity systems and/or hydrogen, all of which add significant cost. The need for storage can be ameliorated to some degree by geographically dispersed power generation, provided transmission capacity is available. A major source of flexibility is the use of excess electricity at times of high renewable generation for electrolytic hydrogen production and the final stage of steelmaking using electric arc technology.

Emerging policy issues

Australia has very large reserves of several metals that underpin the modern global economy, including iron and aluminum. As such, Australia will remain a leading global commodity supplier for these commodities. Australia is already a leading supplier of lithium and manganese, which are essential to some existing and emerging energy storage technologies. The rare earth resource in Australia is huge, but its current supply is relatively small. Cobalt, vanadium and other, rarer critical metals are also relatively abundant, and the mining of these will help diversify the resource sector in terms of both commodities and geographical dispersion, and that should bring new opportunities to rural and remote regions.

In a zero-carbon world in which primary energy is sourced mainly from renewable resources, Australia will have significant competitive advantage as a potential home for metal refining and processing. Consideration of future large power demand centres associated with mineral processing will be important to planning a reliable, least-cost, national renewable energy system. Developing the local mineral-refining capacity will also help mitigate global supply risks, which are emerging for many of the critical metals, such as the REEs. With significant opportunity for the recovery of important companion metals such as cobalt by reprocessing of existing mine wastes, there is an opportunity for remediation of past mining activity.

Despite these advantages there will be challenges in realising the potential, particularly on pathways of aggressive decarbonisation. These include the global competition for capital and human resources.

While the cheap energy advantage afforded to Australian operations in a net-zero world is well recognised, we are not yet in that world. In the Australian energy markets, the marginal cost of electricity is historically set by gas pricing. Since the opening-up of the eastern Australian gas market to international gas pricing in 2015, domestic electricity prices have been de facto fixed to global gas price fluctuations. Consequently, Australia is currently a relatively high-energy-cost country. In this environment, encouraging large capital allocations into energy-intensive mineral processing in anticipation of cheap energy emerging on a decadal timescale will necessarily require some significant transitional financial incentives.

The research challenges in realising the benefit of Australian critical mineral endowments across the full supply chain remain immense and will require dedicated funding. This is now recognised with the Department of Industry, Science, Energy and Resources establishing a Critical Minerals Facilitation Office, including a range of funding initiatives. This includes an initial funding package for research and development of $50 million directed to CSIRO and Geoscience Australia as well as a raft of other measures through programs such as the CRC and NCRIS.

It is important to realise that these funding arrangements build on a strong historical record of higher education investment in relevant disciplines. That is no longer guaranteed. With a strong history of resource development, Australia has had ready access to highly trained professionals in fields such as geophysics, geology, metallurgy and mining engineering, as well as to world-class university research. This is no longer the case. Training in geophysics and metallurgy is close to extinction in this country, and with it the university-related research in these fields in which Australia has been a world leader in the past. It is bewildering that in a country so economically dependent on its earth resources, its principal research agency, the Australian Research Council, now allocates an order of magnitude more funding for the study of the physics of remote stars than it does for the physics of our own planet. The global pandemic has been particularly hard on the earth resource disciplines. In the face of a federal government that has appeared to be deliberately degrading university education and research, the higher education sector has clearly failed to see long-term advantage in resource sector training and research. Universities have socialised the loss from international fee-paying students (mainly in disciplines such as business to and economics) across all disciplines, and with weak domestic student enrolments this has seen devastation for the geosciences. Not long ago the Research School of Earth Science at the ANU ranked in the top five international research institutes in the field. It has been savaged, with some of Australia's most celebrated scientists forced into early retirement. In a panicked reaction to the pandemic, geosciences at University of Melbourne suffered a similar fate as it was cut harder than any other discipline, despite negligible international student exposure. Internationally recognised geoscience departments at Macquarie and Newcastle Universities were effectively closed, and with a few notable exceptions most other schools were downsized in attempts to balance the loss of international fee-paying students.

It seems impossible to conceive how disciplines such as geophysics and metallurgy can survive in the Australian university system if current funding arrangements remain directed by the whims of eighteen-year-olds' enrolments and the ambitions of international students. Some of our largest resource companies, such as BHP, are alert to and alarmed by the critical nature of this issue and are offering special graduate student internship programs to entice students to engage with the challenge. But this begs the question: will there be anyone left to train them in fields such as geophysics and metallurgy? If Australia is to realise its potential as a Superpower by expanding its supply of metals for the global energy transition, a policy imperative for the federal government should be to redress the current higher education funding arrangements to secure critical mass in these disciplines so essential to Australia's future national benefit.