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Addressing Vulnerabilities in the Supply Chain of Critical Minerals

Report

CEEW THE COUNCIL

iea International Energy Agency

UCDAVIS
India ZEV Research Centre
Institute of Transportation Studies

Acknowledgment

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Dated: 27th March, 2023

MESSAGE

Climate change poses an existential threat to living beings on Earth. The frequency and intensity of extreme climatic events have only increased recently. The decarbonisation of the power, transport and industrial sectors needs to happen urgently and the energy transition needs to be accelerated.

There can be no energy transition without critical minerals. Clean energy technologies use minerals which are geographically concentrated with limited availability. The annual demand for many minerals will increase multifold in the coming years and if not planned well, there can be a supply-demand mismatch. Identifying strategies for mitigating disruptions in the critical mineral supply chains is essential. The G20 countries are responsible for most of the global emissions but are also spearheading the effort to mitigate climate change. Many technologies relevant to energy transition are being developed and deployed in the G20 countries. In this context, G20 countries must take leadership to strengthen the critical mineral value chain to ensure an uninterrupted global energy transition. This is a generational opportunity.

Mineral exploration, mining and processing have long lead times and require long-term planning. We hope that this report by the Council on Energy, Environment, and Water (CEEW), the International Energy Agency (IEA), the University of California, Davis, and the World Resources Institute (WRI) will inform the key decision-makers about the challenges and opportunities which need to be addressed and tapped. Implementing the key recommendations on periodic tracking of the critical mineral value chain, sharing and co-development of technology, supporting alternative technologies with lower mineral intensity and scaling up circularity can provide the much-needed momentum for the sector.

I hope the report will mainstream the conversation on building, scaling and diversifying the critical mineral value chain.

Vivek Bharadwaj

(Vivek Bharadwaj)

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Preface

Dr Arunabha Ghosh
CEO, CEEW

The pace of the global energy transition could determine the world's ability to keep temperature rise to well below 2°C above pre-industrial temperatures. But the transition will not come without its challenges. Modern low-carbon energy systems are replacing fuel-hungry technologies with mineral-hungry ones. The demand for minerals needed to support a low-carbon future will have a major impact on global commodity supply chains. Countries will need to manage this demand realignment if they are to secure their net-zero futures.

Minerals are, by their very nature, unequally distributed across the world. Many countries that will most need these minerals to fuel their energy transition lack sufficient domestic resources. Other countries are blessed with vast deposits, but these often sit within socially and ecologically sensitive areas. The global community bears a responsibility to ensure that these minerals reach the markets that need them most, while avoiding the ravages of the past by protecting the most vulnerable against unjust resource exploitation.

The main message of this report is that the world needs to act, and quickly. Any decision taken today will take decades to make a noticeable difference in global commodity markets. The world needs many more responsibly-developed mines to satiate its imminent demand for critical minerals. It also needs to spend more on identifying new resources. And perhaps most importantly, the world needs a strategy to reduce demand by developing a circular economy to substitute more abundant alternatives for critical minerals.

This new world of minerals need not be a lawless "Wild West". Rather, we can build a rules-based, multilateral approach to securing minerals for our low-carbon future. Multilateralism will require the largest economies to look beyond the next commodity price cycle and, instead, take a more strategic stand focusing on a sustainable future. A sustainable future that brings on-board smaller countries with vast natural resources in a way that is constructive rather than exploitative.

International collaboration on critical minerals has the potential to go beyond simply supporting a low-carbon future. This new mineral paradigm could be a boon for countries, particularly in the Global South, with rich mineral resources. But these countries will need to be wary of the resource curse. Investments in new projects need to be accompanied by skill-building, technology transfers and the participation of local communities. Whether minerals will put a spanner in the energy transition, or act as sustainable economic drivers, will depend on the decision the global community starts making today.

The global transition to low-carbon technologies is leading to growing demand for critical minerals. It is becoming important for policymakers, industry leaders and researchers to work together to ensure the sustainable and responsible production and use of these essential resources.

Image: Alamy

Contents

Figures

Tables and boxes

Acronyms and abbreviations

Ag	silver
Al	aluminium
APS	Announced Pledges Scenario
As	arsenic
a-Si	amorphous silicon
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
Au	gold
B	boron
B20	Business 20
Ba	barium
Be	beryllium
Bi	bismuth
C	carbon
CAIT	Climate Analysis Indicator Tool
CdTe	cadmium-telluride
Ce	cerium
CIGS	copper-indium-gallium-diselenide-disulphide
Co	cobalt
CO2	carbon dioxide
COP	Conference of Parties
Cr	chromium
CRM	critical raw materials
Cs	caesium
c-Si	crystalline silicon
CSP	concentrating solar power
Cu	copper
DLE	direct lithium extraction
DLP	direct lithium to product
DRC	Democratic Republic of Congo
Dy	dysprosium
EoL RIR	end-of-life recycling input rates
Er	erbium
Eu	europium
EV	electric vehicles
EW	electrowinning
F	fluorine
FC	Fuel cell
Fe	iron
Ga	gallium
GATT	General Agreement on Tariffs and Trade
Gd	gadolinium
Ge	germanium
GHG	greenhouse gas
GIS	Geographical Information System
Gt	giga tonne
GW	giga watts
Hf	hafnium
HLT	hard-rock lithium
Ho	holmium
HPAL	high-pressure acid leaching
IEA	International Energy Agency
In	indium
IPCC	Intergovernmental Panel on Climate Change
Ir	iridium
IRENA	International Renewable Energy Agency
IRTC	International Round Table on Materials Criticality
kt	kilo tonnes

La	lanthanum
Li	lithium
LIB	lithium-ion battery
Lu	lutetium
Mg	magnesium
mg/W	milligram per watt
Mn	manganese
Mo	molybdenum
MT	metric tonnes
Nb	niobium
Nd	neodymium
Nd-Fe-B	neodymium-iron-boron
Ni	nickel
Ni/MH	nickel metal hydride
NMC	nickel manganese cobalt
NZE	net zero emissions
P	phosphorus
Pb	lead
Pd	palladium
PGMs	platinum group metals
PM	permanent magnets
ppm	parts per million
Pr	praseodymium
Pt	platinum
PV	photovoltaic
R&D	research and development
Rb	rubidium
Re	rhenium
REE	rare earth elements
Rh	rhodium
Ru	ruthenium
Sb	antimony
Sc	scandium
SDGs	Sustainable Development Goals
Se	selenium
Si	silicon
Sm	samarium
Sn	tin
Sr	strontium
STAX	spheroidal, thin, aggregated and expanded graphite
STEPS	Stated Policies Scenario
SX	solvent extraction
Ta	tantalum
Tb	terbium
Te	tellurium
TEMPEST	Telecommunications Electronics Material Protected from Emanating Spurious Transmissions
Ti	titanium
Tl	thallium
Tm	thulium
TWh	terawatt hour
U	uranium
UN	United Nations
USGS	United States Geological Survey
V	vanadium
W	tungsten
WTO	World Trade Organization
Y	yttrium
Yb	ytterbium
Zn	zinc
Zr	zirconium

The need of the hour is to diversify the mineral value-chain and enable regional and local ecosystems through global mandates that encourage local recovery of critical minerals. This would pave the way for equitable access to critical minerals.

Image: iStock

Executive summary

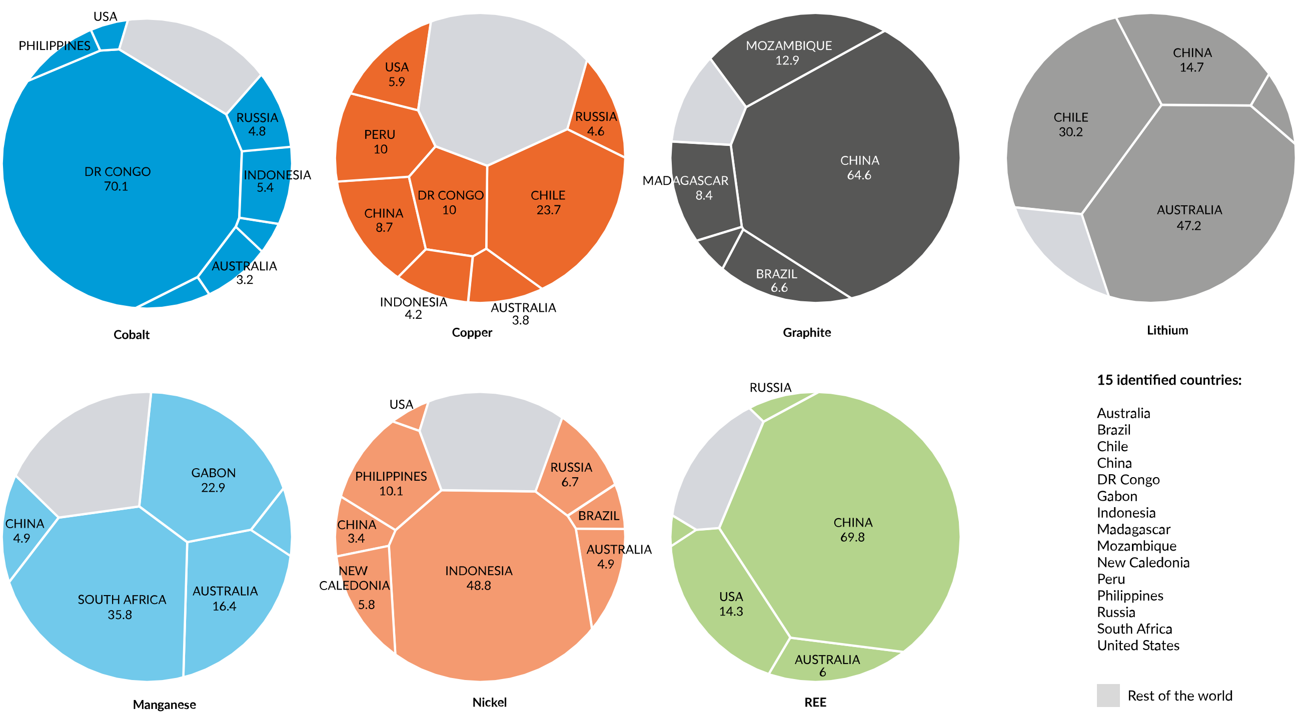
The theme of India's G20 presidency in 2023 – "*Vasudhaiva Kutumbakam*" – affirms the value of all life – humans, animals, plants, and microorganisms – and their interconnectedness. Energy in all its forms is the central driver for this interconnectedness. Our energy usage across centuries is a key cause of human-induced climate change. While mitigation and adaptation efforts have reduced vulnerability, there is still a lot more to be achieved. Though the current energy use is a significant contributor to the problem, sustainable energy transitions are the key to the solution.

Within this framing, it is also instructive to note that the G20 countries are responsible for more than 75 per cent of the total greenhouse gas (GHG) emissions in the world and 78 per cent of global CO_2 emissions – the key contributor to global warming. Concerted efforts by this group towards realising sustainable and clean energy transitions will widen and increase the demand for minerals. This means that the traditional paradigm of energy security, which so far has been limited to fossil fuel supply disruptions and price spikes, will need to be reassessed, and the vulnerabilities associated with mining minerals will have to be considered.

Our paper analyses the framework for establishing criticality of minerals. It found that there is no set list of critical minerals across different geographies, and each country identifies critical minerals based on their level of economic development, nationally available resources, and technology choice. Despite this, certain minerals are more commonly considered critical across different geographies. With respect to technologies in the energy sector, the paper found that certain minerals are commonly used across different applications and uses. These include lithium, cobalt, nickel, copper, manganese, graphite and rare earths.

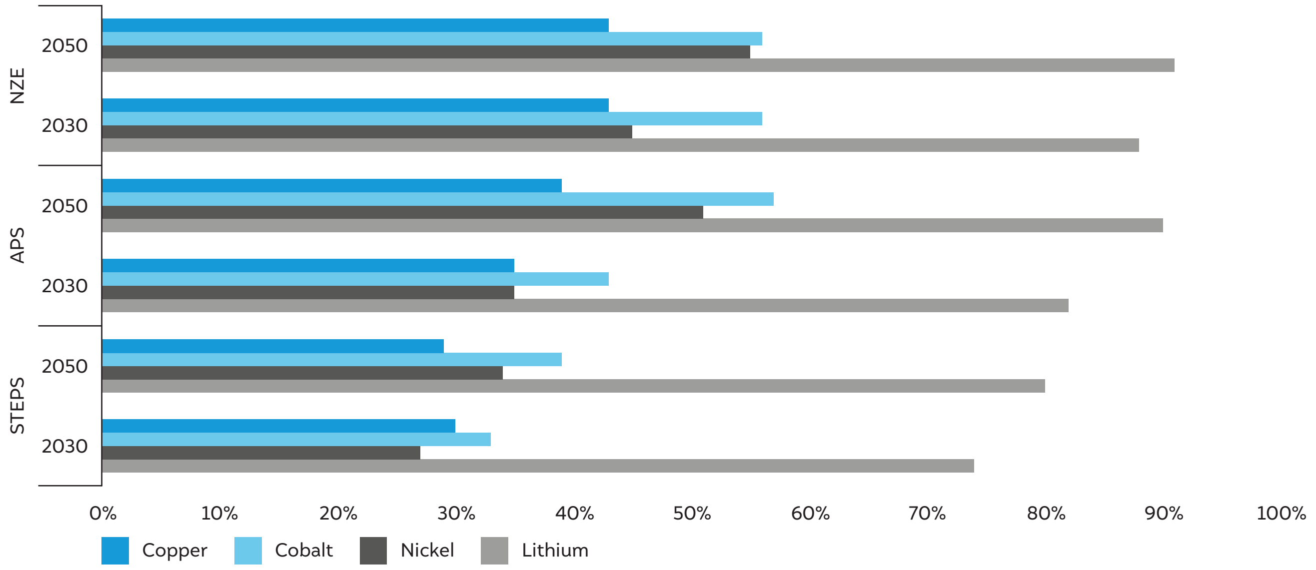
Fig ES 1 **The production of minerals needed for low-carbon technologies is concentrated in a handful of countries**

Share of mine production in 2022 (in %)



Source: USGS 2023

Figure ES2 Focus clean technologies make up a significant share of total demand for certain minerals



Source: IEA analysis

The paper shows that resources and reserves, and therefore production, for most minerals are geographically concentrated. For example, Bolivia has the world's largest deposits of lithium (despite not mining it), while 46 per cent of the world's cobalt reserves is found in the Democratic Republic of Congo. China accounts for ~79 per cent of natural graphite production while nearly 50 per cent of the world's lithium is mined in Australia. Further, investment needs are not being adequately met to keep pace with the increasing demand and longer lead times of mining project development. Regulatory changes are further affecting investment outlooks for companies. A handful of countries, such as Australia, Indonesia and Mozambique have driven the increase in the production of these minerals in recent years. For some minerals such as copper, cobalt and nickel, current mining production is over two per cent of identified reserves. As the mining of these and other minerals grows in the coming years, inefficiencies in existing mining technologies could lead to an increase in the emissions intensity of mineral mining, especially since issues related to intellectual property rights limit the sharing of more efficient technologies. Delays in implementing recycling practices and regulations also have the potential to impact the demand and supply balance over the next few decades.

The paper finds that the demand for critical minerals, based on their use in batteries (electric vehicles [EVs] and grid storage), solar photovoltaics (PV), wind turbines, and transmission wires, will rise significantly in the future.

The analyses show that the focus on clean technologies (solar, wind, batteries for EV and grid storage, and grid infrastructure) will account for the majority of the lithium demand (80–91 per cent) by 2050. Nickel demand from clean technologies is estimated to between 34-55 per cent of the total demand by 2050, while copper demand is estimated to range 29–43 per cent by 2050. Cobalt demand from the clean energy sector is expected to cross 55 per cent of the total demand in 2050. This provides a strong indication of the dependence of key technologies on these minerals.

To meet the future demand, the paper examines new developments on exploration, mining, and processing of critical minerals. This includes new technologies to detect mineral deposits and improving current mining practices to increase production. It also discusses investing in technologies that avoid over-dependence or reduce mineral demand. It details examples such as replacing cobalt with other minerals in battery cathode materials, replacing graphite with silicon for battery anodes, developing rare earth–free EV motors and wind turbines and reducing the silver content in passive emitter rear contact (PERC) cells for solar PVs. Additionally, the paper talks about extending product use (second-life application for batteries for instance) and mandating repairs and services provision for extending the life of various consumer goods along with increasing recycling and recovery from discarded products. Based on this in-depth assessment, the paper identifies two key priorities for G20 countries to address vulnerability with respect to critical mineral demand for clean energy technologies. These are as follows:

First, develop a shared vision on critical minerals for increasing the supply of minerals: We recommend specific action points to increase mineral supply. There is an urgent need to institutionalise periodic assessments of the critical mineral value chain. The G20 should also support investments in, and the development of, new exploration and mining technologies. Finally, the group must examine the creation of a strategic stockpile of critical minerals.

Second, enhance global mineral security by scaling up reduce and reuse efforts: The G20 must lead the charge in focused R&D efforts to improve existing technologies from a resource-efficiency perspective and must support the development of alternative technologies that reduce dependence on critical minerals. The G20 must also provide an enabling ecosystem that nurtures these alternatives through dedicated public procurement plans, standardisation regimes, and a harmonising approach to these technologies from a trade perspective. Lastly, the G20 must increase focus on recycling of products and recovery of minerals by co-developing mineral recovery technologies which are currently concentrated. Enabling regional and local ecosystems to recover through global mandates that encourage local recovery would pave the way for equitable access to recovered minerals.

1. Introduction

The world today still relies heavily on fossil fuels. In 2021, 77 per cent of the primary energy supply came from oil, coal and natural gas. A complete overhaul of today's energy system is required to meet the Paris commitments (IEA 2023). This includes behavioural change concerning consumption, increasing energy efficiency, and investment in mature and new clean energy technologies.

Clean energy investments now represent 70 per cent of the growth in total energy sector investments, reaching USD 1.4 trillion in 2022. This is an increase of 10 per cent as compared to 2021. Further, these investments are fuelling investments in clean energy technology manufacturing which many governments across the world are aiming to leverage (IEA 2023).

The mineral requirement scale up of clean energy technologies is increasing since the last decade. This trend is only going to increase as the transition begins to materially impact global energy supply. For instance, constructing a typical electric car requires six times the mineral inputs than when compared to a conventional vehicle. Making an onshore wind plant requires nine times more mineral resources than a gas-fired plant of the same capacity (IEA 2021). This also reshapes our energy security paradigm, given these minerals and their supply chains are geographically more concentrated than their fossil fuel-based counterparts. The top five countries together account for over 70 per cent of global capacity for manufacturing key clean energy technologies. Concentration at any point along a supply chain makes the entire supply chain vulnerable to incidents, be they related to an individual country's policy choices, natural disasters, technical failures or company decisions. In addition, issues such as longer lead times for mine development, complex mineral processing technologies, high investments and dedicated infrastructure, declining resource quality, higher exposure to climate risks all lead to concerns over potential increase in price volatility and market constraints which will impact future transition.

Accordingly, this report seeks to break down one part of this complex supply chain, i.e., critical minerals. It focusses primarily on lithium, cobalt, nickel, copper, manganese, graphite and rare earth elements (REE). Of all the minerals utilised in clean energy systems, these seven are likely to see the disruptions with respect to their availability, processing, and price due to increasing demand. For example, lithium demand increases the fastest between now and 2030 driven largely by EV batteries and grid storage. This report discusses the demand for these minerals given deployment of clean energy. It provides a mapping of reserves and production. It also provides an insight on creating a criticality index for those countries which are still framing their own index. Finally, it goes on to illustrate ongoing technologies and R&D that can help reduce our dependency on these minerals while also improving the circular nature of our consumption.

2. Mineral use in low-carbon technologies

Given the increasing focus on decarbonisation, the global demand for the minerals used in the technologies required for realising a low-carbon economy will increase significantly in the coming years.

> **Over 70% of the global capacity for manufacturing clean technologies is concentrated in only 5 countries.**

Table 1 Minerals used to develop different low-carbon technologies (LCTs)

LCT	Copper	Cobalt	Nickel	Lithium	REEs	Chromium	Zinc	PGMs	Aluminium
Solar PV	●								●
Wind	●		●		●	●	●		●
Hydro	●					●	●		●
CSP	●		●			●	●		●
Bioenergy	●						●		●
Geothermal			●			●			
Nuclear	●		●			●			
Electricity networks	●								
EVs & battery storage	●	●	●	●	●				●
Hydrogen			●		●			●	●

Source: Authors' adaptation from multiple sources

2.1 Low-carbon energy generation

Solar PVs

Copper is used in solar cells to create conductive gridlines that carry electrical current generated by the solar cell. These gridlines are typically made of thin copper wires or ribbons that are placed on top of the solar cell surface. Copper is a good conductor of electricity and is highly durable and corrosion resistant, making it ideal for use in solar cells. Aluminium is used in the frame and casing of solar panels as well as in the wiring and connections between panels. Aluminium is lightweight and has a good strength-to-weight ratio, making it ideal for use in the supporting structure of the solar panel (Assad, Nazari, and Rosen 2021).

Wind

Wind turbines often utilise PM generators, particularly, direct-drive permanent magnet synchronous generators (PMSG), because of their low weight and high power density. These PMSGs are made using NdFeB magnets, which are highly potent magnetic materials and contain REEs such as neodymium (Nd), praseodymium (Pr), and dysprosium (Dy) (IEA 2022b).

Hydropower

Copper is used in the production of hydropower generators, turbines, and transformers. It is an excellent conductor of electricity and is essential for the transmission of electricity. Aluminium is used in the construction of transmission lines, which are used to transport electricity from hydropower plants to the grid. Rare earth elements are used in the production of permanent magnets that are used in generators and turbines. These magnets are essential for the efficient production of hydropower (Quaranta and Davies 2022).

Concentrated solar power (CSP)

The expansion of concentrated solar power is expected to increase the demand for several minerals. Copper is used in the production of wires and cables that are used to connect components in the CSP system. Tellurium is used in the production of high-efficiency solar cells. Nickel is used in the production of CSP components, including heat exchangers and storage tanks. Cobalt is used in the production of high-temperature alloys and CSP components, including receivers and heat exchangers (Caccia, et al. 2018).

Geothermal

Nickel is used in the production of geothermal well casing, which is used to line the borehole drilled into the earth's surface to access the geothermal reservoir. Nickel alloys, such as Inconel, are commonly used in high-temperature and high-pressure geothermal wells due to their excellent corrosion resistance, high strength, and good fatigue resistance.

Chromium is used in the production of geothermal heat exchangers, which transfer heat from the geothermal fluid to the power generation system. Chromium alloys, such as stainless steel, are commonly used in geothermal heat exchangers due to their good corrosion resistance and high temperature strength. Chromium also helps prevent scaling and corrosion, which can reduce the efficiency and lifespan of the geothermal power plant (Assad, Nazari, and Rosen 2021).

2.2 Low-carbon energy systems

2.2.1 Electricity networks

Copper is used in various components of electrical networks, including transmission lines, distribution lines, transformers, and electrical equipment. Copper is an excellent conductor of electricity, which means that it can carry electrical current with very little resistance. This is important for minimising energy losses and ensuring the efficient transmission of electricity over long distances. Copper wires are also used in transformers to step up or step down the voltage of electrical current as it is transmitted through the network. Copper is also used in electrical equipment, including motors, generators, switchgear, and circuit breakers. Copper is a good conductor of heat, which means that it can efficiently dissipate the heat generated by electrical equipment, helping prevent overheating and potential failures. Copper is also used in grounding systems, which help protect people and equipment from electrical hazards by providing a safe path for electrical current to flow in the event of a fault or lightning strike (Copper Alliance 2022).

2.2.2 EVs and energy storage

Lithium-ion batteries (LIB) are a front-runner energy storage technology used in several applications, and their demand and future uptake will be dominated by Electric Vehicles (EVs) and stationary energy storage applications. LIB contain several metals used in the cell anodes, cathodes, electrolytes, and separators, where some of the metals are transitioning towards becoming critical materials due to possible raw material scarcity and geopolitical conditions (Blengini, et al. 2020).

Traction motors: Permanent magnets (PM) synchronous-traction motors that are widely used in EVs contain neodymium-iron-boron (NdFeB) magnets. NdFeB magnets contain REEs such as neodymium (Nd), praseodymium (Pr), and dysprosium (Dy). Alternatives to PM-based motors include induction motors, which contain high quantities of copper (Raminosoa, et al. 2020).

2.2.3 Hydrogen

Fuel cells: Fuel cell (FC) technology is can be used in the transportation and power generation industry. With the increasing demand for FC technology, the demand for certain materials used in FC is expected to increase significantly (Tokimatsu, etal. 2018). Platinum is used in proton exchange membrane (PEM) fuel cells, which are used to convert hydrogen to electricity. It is used as a catalyst in the fuel cell's electrode, facilitating the reaction between hydrogen and oxygen. Nickel is used as a catalyst in the production of hydrogen through steam-methane reforming. Cobalt is used in the production of hydrogen through electrolysis. Cobalt is also used in the electrode of the electrolysis cell. Molybdenum is used in the production of high-strength alloys used in hydrogen storage tanks. Rare earth elements such as neodymium, dysprosium, and praseodymium are used in the production of hydrogen FC vehicles' electric motors. They are also used in the production of electrolysis cells, which are used to produce hydrogen from water. Titanium is used in the production of hydrogen storage tanks and as a component in the production of PEM fuel cells (Tokimatsu, et al. 2018).

Electrolysers: Electrolysers are used for producing hydrogen from electricity. The manufacture of electrolysers requires the use of vital minerals such as platinum, iridium, yttrium, zirconium, lanthanum, and nickel (Tokimatsu, et al. 2018).

Table 2 Raw materials (selected) used in energy storage technologies

LIB (Cell Components)	Raw materials
Cathode	Li, Co, Mn, Ni,
Anode	Graphite, Si (future), Ti (future), Nb (future)
Electrolyte	Li
Current collector	Cu, Al

Source: Authors adaptation from multiple sources

3. Criticality assessment of minerals needed for the global clean energy transition

Assessing the degree of 'mineral criticality' can aid in comprehending the availability and accessibility of the minerals and metals needed to facilitate the transition to low-carbon technologies, particularly in the energy and transport domains. Moreover, criticality assessments can help inform the diversification of the currently concentrated supply chain of some of the key clean energy technologies. A key example is the lithium-ion battery supply chain. The material processing is relatively more geographically concentrated than raw materials reserves and production. This presents a huge opportunity for collaboration to diversify the lithium supply chain (IEA 2022b). Through criticality assessments, policymakers and industry players can make informed decisions regarding investments, trade agreements, collaborative strategies, prioritisation of research projects, and policy agenda, among other things.

3.1 Global critical mineral assessment frameworks and methodologies

Critical mineral assessment is the process of identifying and evaluating the risks associated with the supply and demand of raw materials that are essential to a particular industry or application (Schrijvers et al. 2020) technology, or company. The general framework for a critical raw material assessment can be broken down into the following steps (Kim, etal. 2019; Gupta, Biswas, and Ganesan 2016) it is essential to derive the weights using a scientific methodology quantitatively. We applied a fuzzy analytic hierarchy process (AHP)

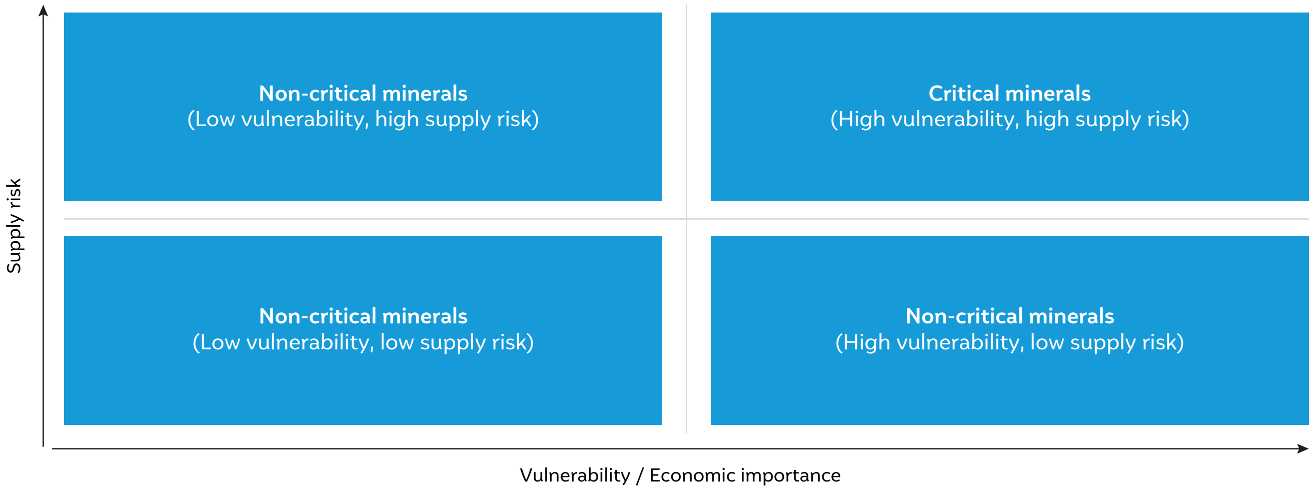
- **Define the scope**: Identify the critical minerals and the industry or application that they are essential to. Define the scope of the assessment, including the timeframe and geographic location.
- **Identify sources**: Identify sources for the critical minerals, including their geographic location, suppliers, and supply chains.
- **Assess supply risks**: Evaluate the risks associated with the supply of critical minerals, including availability, price volatility, geopolitical risks, and environmental risks.
- **Assess demand risks**: Evaluate the risks associated with the demand for critical minerals, including changes in technology, regulations, and market trends.
- **Determine criticality level**: Assign a criticality level to each critical mineral based on the combination of its supply and demand risks.
- **Identify mitigation measures**: Identify potential mitigation measures to reduce the risks associated with the supply and demand of critical minerals.
- **Develop an action plan**: Develop an action plan to implement the mitigation measures and monitor the effectiveness of the plan over time.
- **Review and revise**: Periodically review and revise the critical mineral assessment to ensure that it remains up-to-date and relevant.

The specific details of each step may vary depending on the industry or application being assessed and the goals of the assessment. Additionally, the critical mineral assessment framework may be adapted to fit different industries or applications, such as electronics, energy, or construction (Schrijvers et al. 2020).

The most common approach used to map critical minerals is to plot supply risk and vulnerability risk scores in 2D and identify the critical raw materials (CRMs) as given in Figure 2 (Frenzel et al. 2017).

> **Criticality assessments can help inform the diversification of the currently concentrated supply chain of some of the key clean energy technologies.**

Figure 1 Matrix framework for critical mineral vulnerability assessments



Source: Frenzel et al. (2017)

3.2 Status of mineral criticality assessments

Criticality assessments have been conducted by governments, companies, and researchers. Globally, countries such as the USA, Japan, the United Kingdom, and European Union have conducted criticality assessments for materials and minerals (IRTC 2020).

The criticality of mineral resources may vary across countries, depending on factors such as the country's industry mix, national interests, technologies, and market changes. Table 3 lists some of the most used methodologies to evaluate the criticality of minerals along with the motivation for adopting the methodologies, their key features, and the results.

Table 3 Comparison of some of the most used methodologies to assess mineral criticality globally

Method	Motivation	Key features	Result
National Research Council (NRC) methodology	To effectively address how limitations on the availability of nonfuel minerals could affect various sectors of the US economy	Based on a matrix of the raw materials' supply risk and the impacts of supply restrictions	Short-term and long-term supply risks identification.
European Commission's Criticality Assessment (EC-CA) methodology	To understand the role of raw materials in the EU and secure reliable and undistorted access	Identification of potential supply and demand risks and opportunities and assessment of the environmental and social impacts of mineral extraction and processing	Comprehensive assessment, including the economic, environmental, and social impact of critical minerals
Yale methodology	To broaden the range and comprehensiveness of the criticality format used by the US NRC. Through formal peer review, the study aimed to establish that criticality has both practical value and intellectual worth	Based on supply risk, environmental implications, and vulnerability to supply restrictions. The method provides quantitative time-dependent results in the form of a single score indicator (normalised and aggregated), also displayed on a 3D space graph	Provides medium and long-term analysis of 62 metals and metalloids in the periodic table

Method	Motivation	Key features	Result
British Geological Survey (BGS) methodology	To educate policymakers, businesses, and consumers about the importance of expanding the sources of resources beyond earth, increasing recycling efforts, and maximising resource efficiency	Estimates the relative risk of supply for chemical elements, based on seven criteria (each scored 1 to 3). A supply risk index is obtained by adding all criteria score values and normalising the results	Covers a wide range of minerals, excluding those that are not commonly used for commercial purposes. Additionally, some metals, such as yttrium and rubidium, which are obtained as by-products, have been left out because there is not enough information about them
Japan's Resource Strategy (NEDO)	To identify the objectives for developing substitute technologies as part of upcoming national projects	Evaluates strategic minerals according to supply risk, price risk, demand risk, recycling restrictions, and potential usage restrictions utilising 12 indicators. Each indicator is scored from 0 to 3 points.	Comprehensive assessment methods and provides both long and short-term risk analysis

Source: CEEW analysis based on Hackenhaar et al. (2022)

Evaluating the importance of minerals helps to determine the possibility of supply disruptions and the potential impacts on a system, such as a country's economy, a technology, or a business. However, varying results from different studies suggest that criticality assessments could benefit more from having a global unified approach.

Framework elements to calculate criticality score of a mineral

A comprehensive and evidence-based approach is required for assessing mineral criticality quantitatively (Eheliyagoda, Zeng, and Li 2020). While there is no one-size-fits-all methodology, the following factors could be considered:

- **Economic importance:** The contribution of a mineral to the global economy, particularly in terms of its role in the key manufacturing industries of today and tomorrow.
- **Supply risk:** A periodic evaluation of the status of resources and reserves of minerals and the degree of dependence on imports, the concentration of production, and the potential for supply disruption due to geopolitical, environmental, or other factors.
- **Geopolitical risk:** The political stability of key producer countries, the level of dependence on these countries, and the potential for trade restrictions or other forms of political interference.
- **Substitution potential:** The availability and cost of substitutes for the mineral, and the feasibility of replacing it in key applications.
- **Environmental impact:** The environmental and social risks associated with mining and processing the mineral, including land use, water consumption, and pollution.
- **Recycling potential:** The feasibility and economic viability of recycling the mineral from end-of-life products, reducing the need for primary production.
- **Infrastructure for mineral processing:** The accessibility and availability of minerals are pertinent only if the infrastructure to refine and convert to raw material is available.

The framework could be designed to give each of these factors a certain weight or score, depending on their relative importance in the national, regional, or global context. The framework should also be periodically reviewed and updated to reflect changing market conditions and policy priorities. However, it is important to note that no framework can provide a complete or definitive answer, and that other qualitative and contextual factors may need to be considered. A list of elements frequently used to calculate criticality score are given in the Annexure.

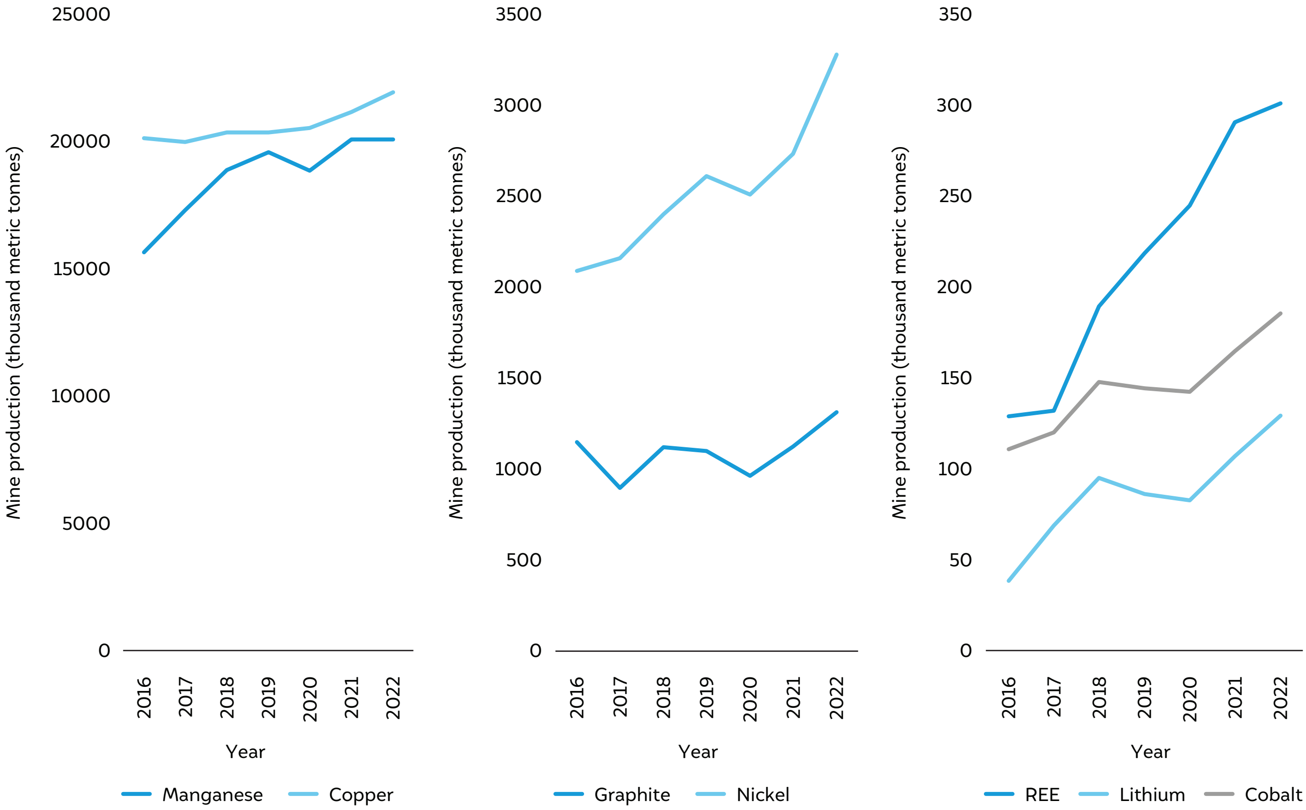
4. Mapping reserves and production of critical minerals

Previous sections have highlighted the growing demand for minerals from various clean energy industries. Already, in the last few years between 2016 and 2022, demand from these industries has led to an uptick in global mining of various key minerals. This section explores key reserves and the mine production trends from 2016 to 2022 of select critical minerals (lithium, nickel, cobalt, copper, manganese, graphite and REEs).

4.1 Global trends in critical minerals for low carbon technologies

For certain minerals such as lithium, REEs, and cobalt, the increase in production in recent years has been substantial: 240 per cent, 134 per cent, and 67 per cent, respectively, between 2016 and 2022. Today, low-carbon manufacturing is a major market for these minerals (USGS 2023). For others, low-carbon technologies still make up a very small portion of overall demand. On the other hand, mining trends can have a significant effect on downstream supply chains due to price changes and supply restrictions. The varying effects of the increased demand from clean energy technologies on various minerals are shown in Figure 2.

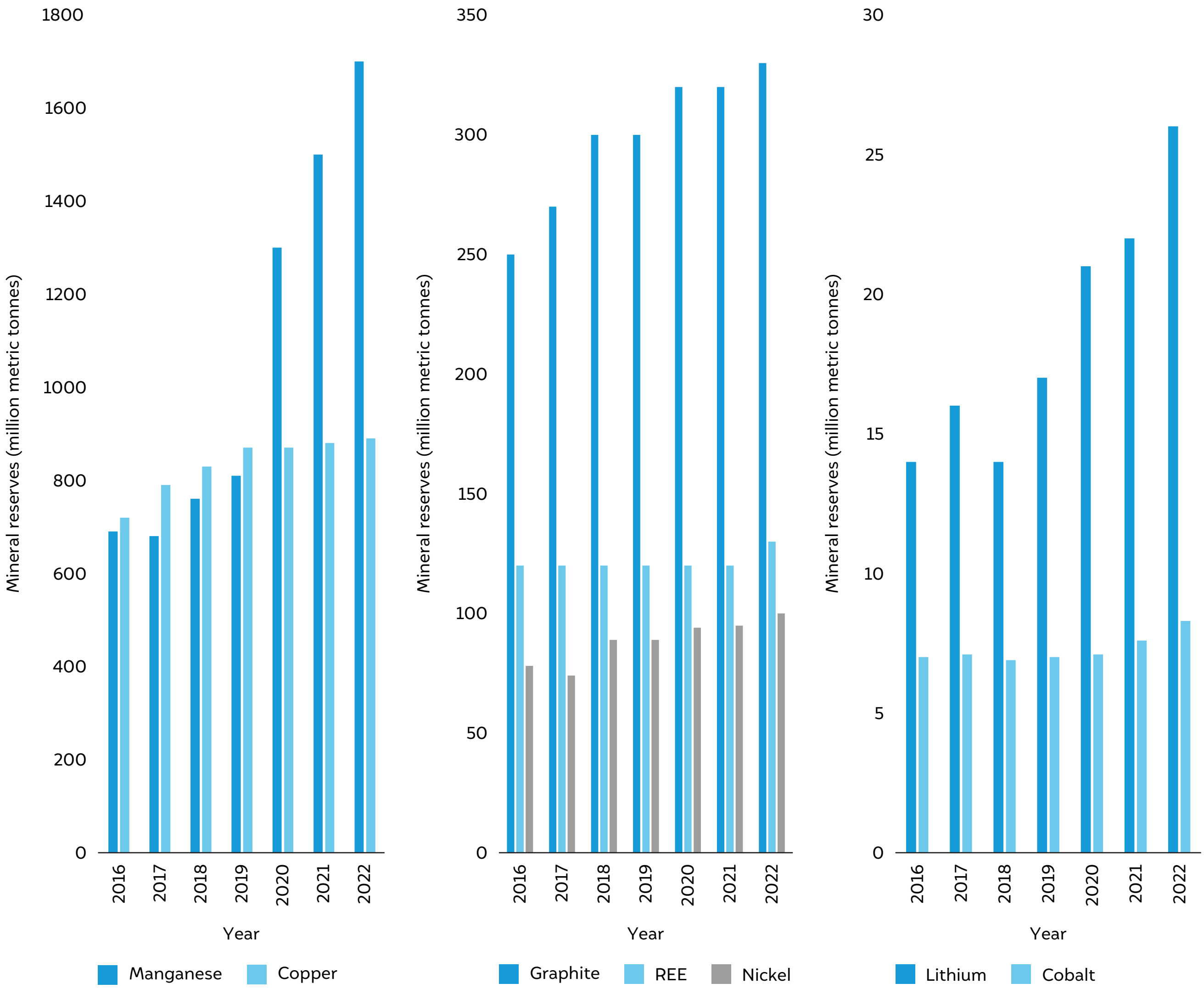
Figure 2 **Minerals such as lithium, REEs, and cobalt have seen a significant increase in mining between 2016 and 2022 due to increased demand from clean technologies and low baseline production**



Source: USGS (2023)

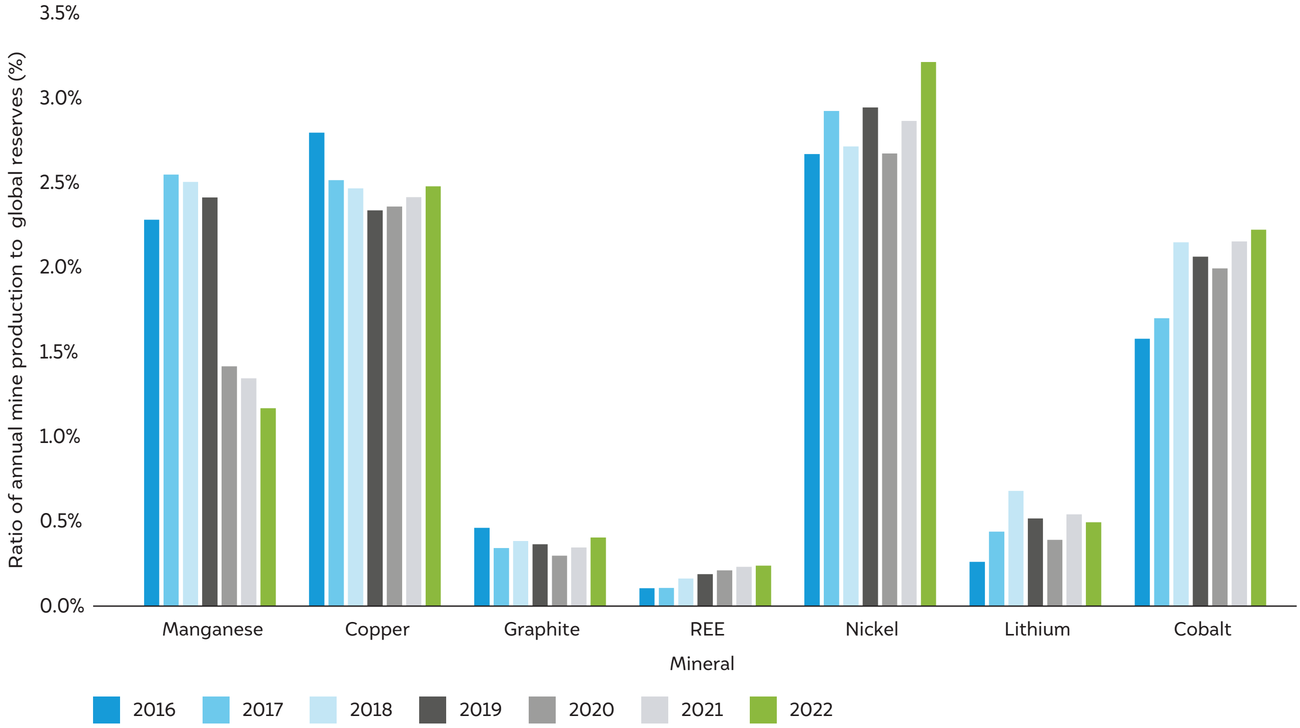
Increasing demand for these minerals has in some cases led to increase in exploration. For manganese and lithium, the available mineral reserves have grown by 150 per cent and 80 per cent, respectively, between 2016 and 2022. For other minerals, the availability of mineral reserves have stayed almost constant. Figure 3 provides the trends in global reserves of select critical minerals. Figure 4 provides the ratio between mine production and reserves for each of the selected minerals – depending on both changing demand and mineral exploration.

Figure 3 **Reserves of minerals such as manganese and lithium have grown substantially from 2016 to 2022, while for other minerals, reserves have stayed constant**



Source: USGS (2023)

Figure 4 For minerals such as copper, nickel, and cobalt, current mine production is already more than 2 per cent of global reserves



Source: USGS (2023)

4.2 The countries at the forefront of mining critical minerals

Most mineral deposits are geographically concentrated, and this is also true of the critical minerals used in low-carbon technologies. This report identifies 15 countries that together globally hold more than 55 per cent of each of the identified critical minerals (Figure 5). These countries were also the source of over 70 per cent of each of the critical minerals in 2022 (Figure 6).

The location of mineral reserves depends on a variety of factors. The existence of a deposit in the form of a resource is necessary but not sufficient. The economic potential of this resource can only be proved by detailed evaluation; thus, country-wise reserve numbers depend significantly on local exploration and evaluation activities (BGS 2023).

Beyond the existence of a reserve, mine production also requires significant investment to set up mines and associated supply chains. As is apparent in Figures 5 and 6, there is a mismatch between the existence of reserves and countries having access to mine production for most minerals. This is further highlighted in Table 4, where we see that some countries have had much greater success than others in developing their domestic reserves.

> **There is a mismatch between the existence of reserves and countries having access to mine production for most minerals.**

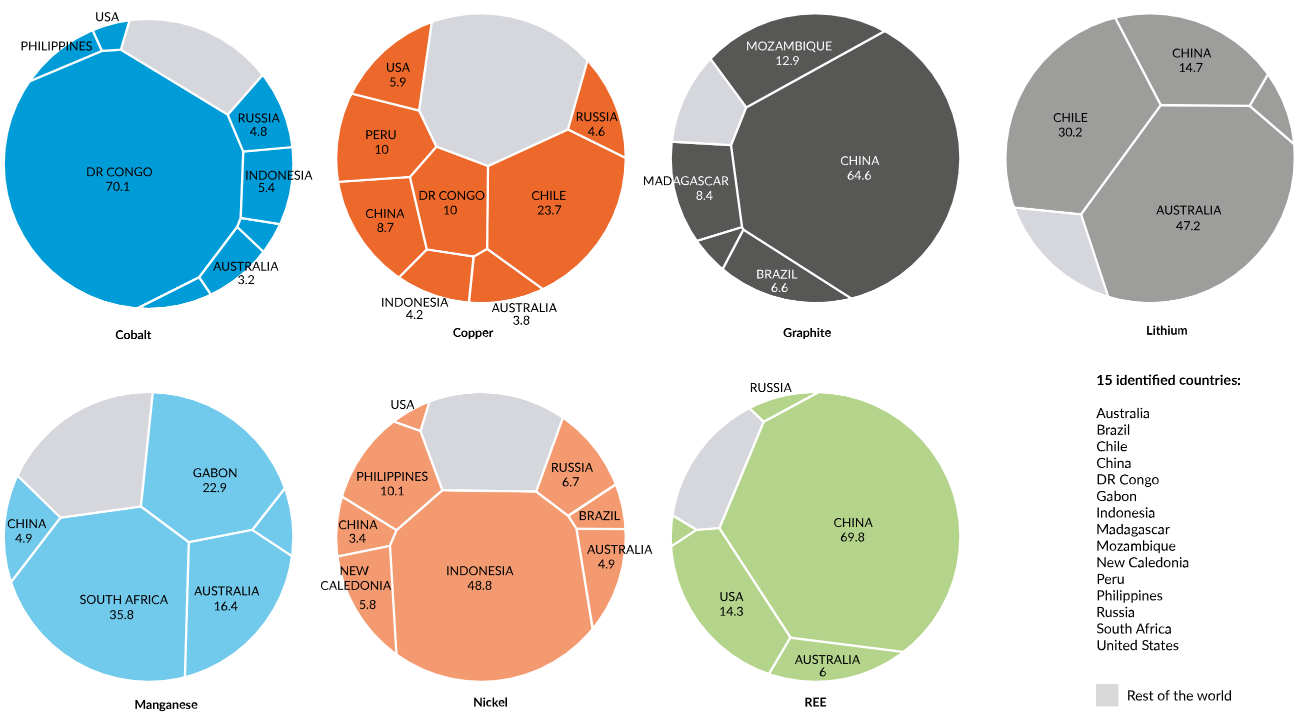
Figure 5 **15 countries are home to at least 55 per cent of each of the identified critical minerals**

Share of global reserves in 2022 (in %)

Source: USGS (2023)

Figure 6 **A handful of countries make up more than 70 per cent of the mine production of all of the identified critical minerals**

Share of mine production in 2022 (in %)



Source: USGS (2023)

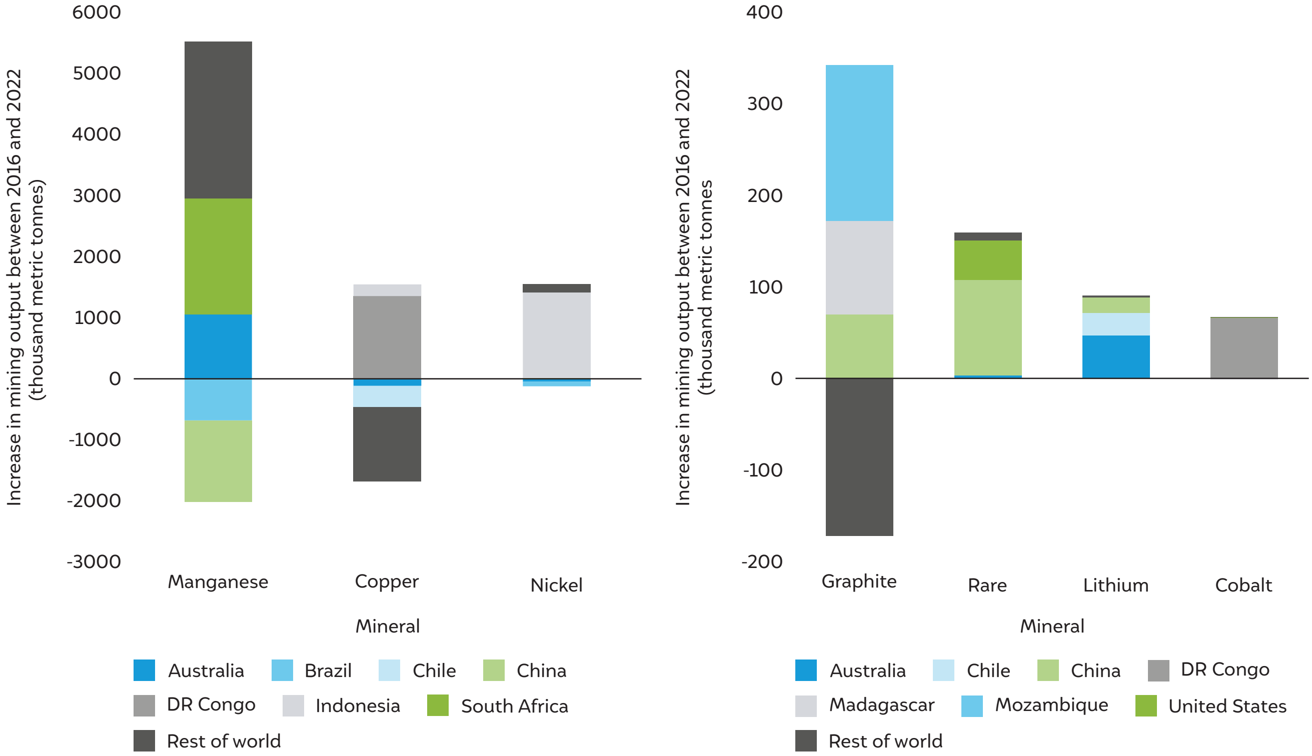
Table 4 Countries have made varying progress in exploiting their domestic mineral reserves

Country	Annual mine production as a percentage of domestic reserves
Indonesia	1.7% (cobalt), 7.6% (nickel)
Australia	0.4% (cobalt), 0.9% (copper), 1.0% (lithium), 1.2% (manganese), 0.8% (nickel)
Russia	1.6% (copper), 2.9% (nickel), 0.0% (REE)
Peru	2.7% (copper)
DR Congo	3.3% (cobalt)
Chile	2.7% (copper), 0.4% (lithium)
Brazil	0.1% (graphite), 0.1% (manganese), 0.5% (nickel), 0.004% (REE)
India	0.042% (REE)
Tanzania	0.044% (graphite)
Vietnam	0.020% (REE)
Turkey	0.003% (graphite)

Source: USGS (2023)

The mineral output of the identified critical minerals has not increased uniformly across countries. Countries such as Australia, China, DR Congo, Indonesia, Mozambique, and South Africa have led the charge, and most of the added capacity in recent years has only been in these geographies (Figure 7).

Figure 7 Countries such as Australia, China, DR Congo, Indonesia, Mozambique, and South Africa have led the charge in increasing the mining output of low-carbon critical minerals from 2016 to 2022



Source: USGS (2023)

5. Critical mineral demand in 2030 and 2050

In this chapter, we estimate the annual demand for these critical minerals for 2030 and 2050, based on the deployment of various clean energy technologies, with a specific focus on EVs, grid storage, and solar and wind transmission. Comprehensive demand estimates for four minerals have been presented in this chapter – lithium, cobalt, copper, and nickel – which are significant across several technologies. Graphite, manganese, and REEs have also been covered for specific technologies.

The analysis focuses on projecting the annual demand for critical minerals for 2030 and 2050 and contextualises it with regards to the availability of these minerals (production and reserves). To forecast the annual demand for critical minerals, we need to understand the growth scenarios in the underlying clean technologies. This report uses the International Energy Agency's (IEA) modelling scenarios and analyses to understand the demand for critical minerals from the clean energy technologies sector.

5.1 The IEA's policy scenarios

The IEA, in its *World Energy Outlook 2022*, has developed three scenarios that provide an overview of the expected energy transition in the upcoming years. These are the Stated Policies Scenario (STEPS), the Announced Pledges Scenario (APS), and the Net Zero Emissions by 2050 scenario (NZE). The modelling approach takes a granular, sector-by-sector look at initiatives to reach energy and climate goals, taking into account not only existing policies and measures but also those under development.

Stated Policies Scenario (STEPS)

The STEPS scenario describes a business-as-usual (BAU) outlook. STEPS explores where the energy system might go without major steering by policymakers. It is not designed to achieve a particular outcome; rather, it takes a sector-by-sector granular look at existing policies and those under development.

Announced Pledges Scenario (APS)

The Announced Pledges Scenario (APS) aims to show to what extent announced ambitions and targets by different countries, including the most recent ones, will enable them to deliver the emissions reductions required to achieve net zero emissions by 2050. It includes all recent major national announcements as of mid-2022 for 2030 targets and longer-term net zero and other pledges.

In the APS, countries are assumed to fully achieve their national targets for 2030 and 2050. The APS assumes that all country-level access to electricity and clean cooking targets are achieved on time and in full. The scenario highlights the "ambition gap" in global emissions that needs to be closed to achieve the 2015 Paris Agreement.

Net Zero Emissions by 2050 Scenario (NZE)

The Net Zero Emissions by 2050 Scenario (NZE) identifies the narrow but achievable pathway for the global energy sector to achieve net zero CO_2 emissions. In this scenario, advanced economies reach net zero much faster than in the other scenarios. This scenario also meets key energy-related United Nations Sustainable Development Goals (SDGs), by achieving universal energy access by 2030 and major improvements in air quality. It is consistent with limiting the global temperature rise to 1.5 °C with no or limited temperature overshoot (with a 50 per cent probability), in line with reductions assessed in the IPCC in its *Sixth Assessment Report* (IEA 2022a).

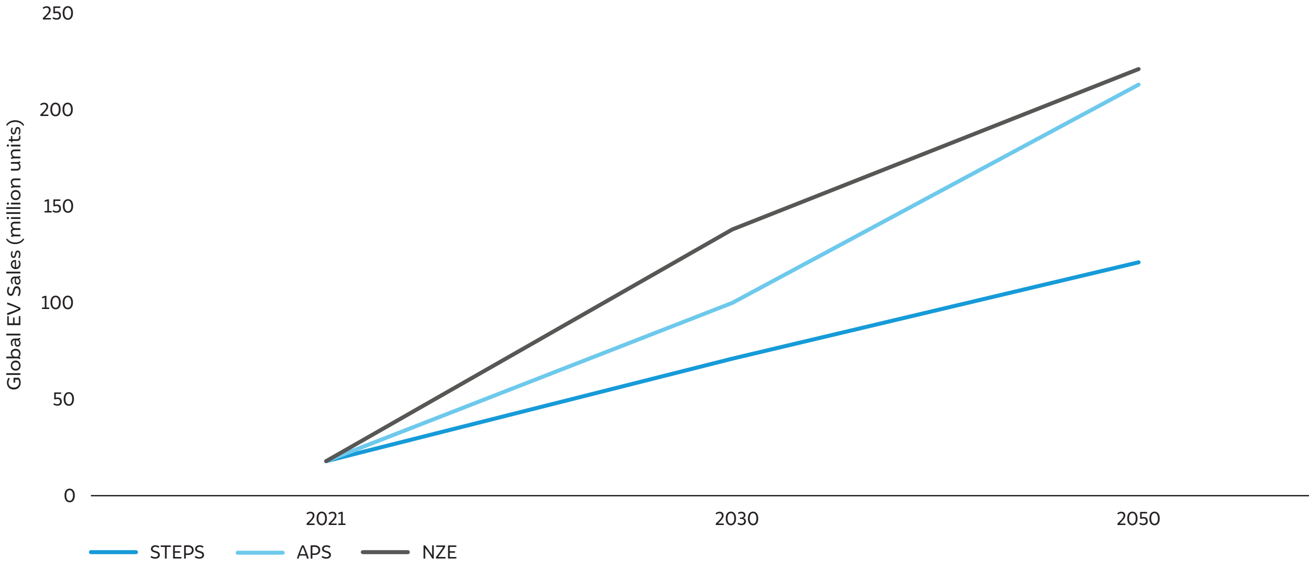
The Net Zero Emissions by 2050 Scenario is built on the following principles:

- The uptake of technologies and emissions reduction options is dictated by costs, technology maturity, policy preferences, and market and country conditions.
- All countries cooperate towards achieving net zero emissions worldwide. This involves all countries participating in efforts to meet the net zero goal, working together in an effective and mutually beneficial way, and recognising the different stages of economic development of countries and regions, and the importance of ensuring a just transition.
- An orderly transition occurs across the energy sector. This includes ensuring the security of fuel and electricity supplies, minimising stranded assets, and aiming to avoid volatility in energy markets.

Based on the assumptions considered in the three scenarios, the demand and deployment numbers for various sectors and the constituent critical minerals have been developed for the years 2030 and 2050. These figures have been discussed in detail in the following sub-section.

> **This report uses the International Energy Agency's (IEA) modelling scenarios and analyses to understand the demand for critical minerals from the low-carbon technologies.**

Figure 8 Global EV sales across scenarios by 2030 and 2050



Source: IEA analysis

5.2 Projected deployment of key clean energy technologies

Annual capacity additions of the following technologies – EVs, battery storage, solar, wind and transmission were projected under the IEA's STEPS, APS, and NZE scenarios for 2030 and 2050.

Projected EV deployment

Under the APS and NZE scenarios, EV sales are expected to increase from 18 million in 2021 to 100 million and 138 million, respectively, in 2030 and 2050. The share of EVs in total vehicle sales is estimated to increase from 47 per cent in the APS in 2030 to 68 per cent in the NZE in 2030. By 2050, under the APS and NZE, nearly 85–95 per cent of the new vehicles sold are expected to be EVs.

In terms of the share of EV in the total stock of vehicles, while EVs make up about 3 per cent in 2021, they are expected to contribute about 16 per cent by 2030 and about 47 per cent by 2050 in the STEPS scenario. This increases to 74 per cent and 91 per cent of total stock in the APS and NZE scenarios respectively for 2050.

> **Almost all the new vehicles sold in 2050 under APS and NZE scenarios are expected to be electric.**

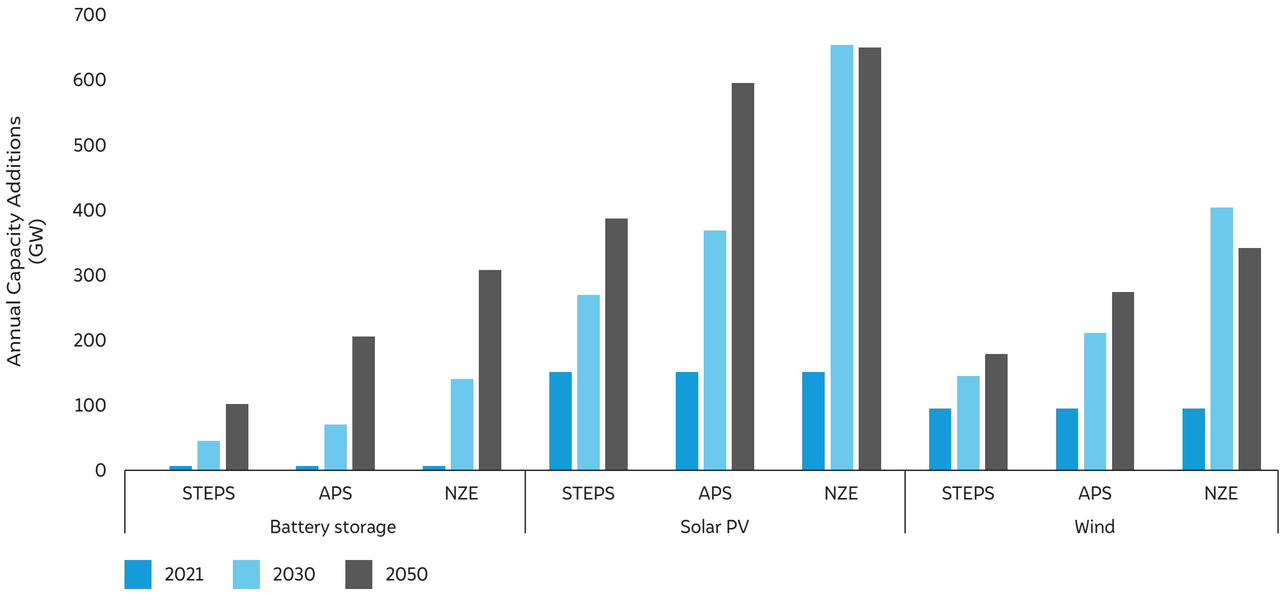
Battery storage, solar PV, and wind installed capacity

The total projected battery demand for storage, and capacity addition for solar PV and wind, are estimated for the three scenarios for 2030 and 2050. In the NZE scenario, the capacity addition of battery storage in 2050 is expected to be 308 GW. The total installed capacity of battery storage was about 27 GW in 2021. Under NZE, this increases to about three times that of STEPS at 3,860 GW in 2050.

Similarly, for solar PV, capacity addition in 2050 under NZE is about one and a half times more than that under STEPS, i.e., 387 GW and 650 GW in 2050. Global installed capacity is expected to increase to 3,020 GW by 2030 and 7,464 GW by 2050 in the STEPS scenario, from 892 GW in 2021. The installed capacity for solar PV is expected to reach 11,065 GW and 15,468 GW in 2050 under the APS and NZE scenarios, respectively.

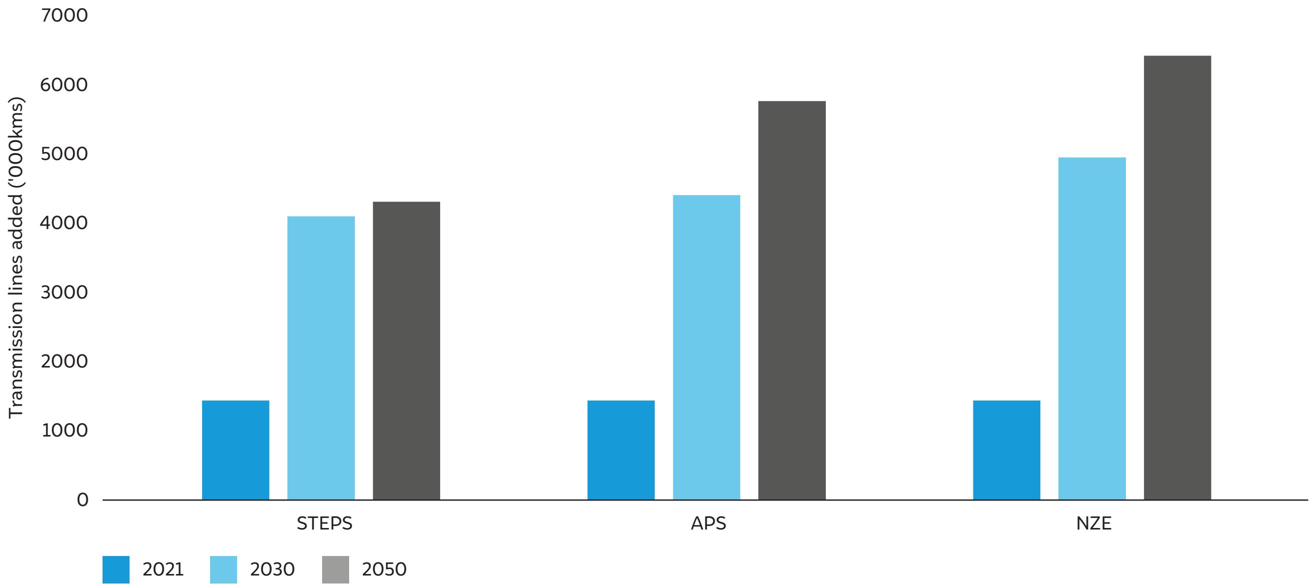
In case of wind, capacity addition in 2050 is expected to be half of that of solar capacity addition in NZE at 342 GW. The installed capacity is expected to increase to 1,830 GW by 2030 and 3,564 GW by 2050 in the STEPS scenario, from 892 GW in 2021. The installed capacity for wind is expected to reach 3,072 GW and 7,795 GW in 2050 under the APS and NZE scenarios, respectively.

Figure 9 Annual battery storage, solar PV, and wind capacity additions (GW)



Source: IEA analysis

Figure 10 Annual transmission lines to be added across scenarios



Source: IEA analysis

Transmission infrastructure

As capacity additions increase across renewables, there will be a need for additional grid infrastructure including transmission lines. In 2021, about 1.4 million km of transmission lines were added, with 4.1 million km and 4.3 million km of transmission lines expected to be added in 2030 and 2050, respectively, as per the STEPS scenario.

In the NZE scenario, additional transmission lines of 4.9 million km and 6.4 million km are expected to be added in 2030 and 2050, respectively.

Of the total capacity, installed capacity of transmission lines is expected to increase from 76 million km in 2021 to about 142 million km by 2050 in the STEPS scenario and about 202 million km in the NZE scenario.

Table 5 Mapping mineral demand across key clean energy technologies

Critical mineral	Electric vehicles	Battery storage	Solar PV	Wind	Grid transmission
Lithium	X	X			
Nickel	X	X	X	X	
Cobalt	X	X			
Copper	X	X	X	X	X
Manganese	X	X			
Graphite	X	X			
Rare earth				X	

Source: IEA and UC Davis analysis

Table 6 Annual mineral demand (kt) across key clean technologies in STEPS, APS and NZE scenario

Mineral	Demand	STEPS		APS		NZE	
		2030	2050	2030	2050	2030	2050
Lithium	Focus clean technologies	240	490	368	1,089	628	1,178
	Total demand	323	611	451	1,209	712	1,299
Nickel	Focus clean technologies	1,058	1,641	1,602	3,364	2,612	3,394
	Total demand	3,912	4,861	4,549	6,538	5,819	6,207
Cobalt	Focus clean technologies	79	146	121	296	205	291
	Total demand	241	372	284	522	367	517
Copper	Focus clean technologies	9,205	10,572	11,198	15,714	15,472	17,209
	Total demand	30,877	36,416	32,061	39,924	35,592	39,754

Source: IEA analysis

5.3 Estimating mineral demand

The four key minerals, i.e., lithium, nickel, cobalt, and copper, were mapped across the clean energy technologies, and based on the mineral content per unit of these technologies, the total mineral demand for 2030 and 2050 was estimated (Dunn et al. 2021). As can be seen from Table 1, all minerals are key for batteries for EV and grid storage, while copper is used across all technologies, followed by nickel, which is relevant to all technologies except grid transmission.

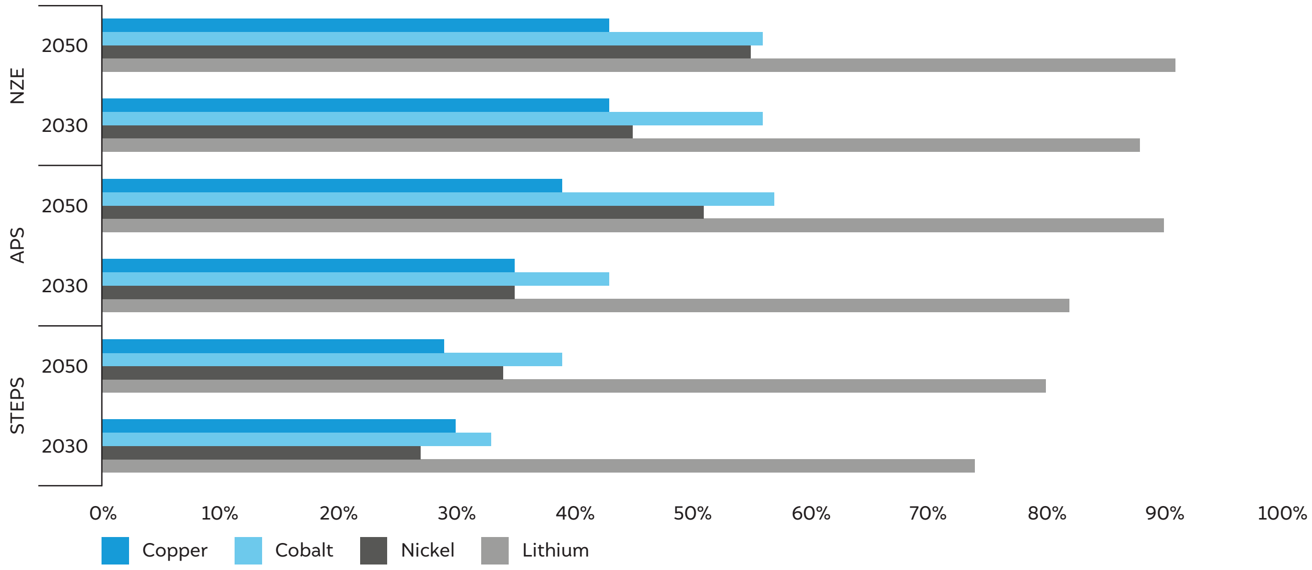
Mineral demand calculations

Based on the deployment projections assessed in the section above, annually, the total mineral in STEPS, in 2030 increases twice as much from 2021. In APS and NZE for 2030 alone, annual mineral demand triples and quadruples respectively. Of this, lithium and nickel demand are primarily driven by an increase in demand for batteries in electric vehicles and grid storage. While cobalt use increases, the real demand for it comes from non-energy sectors including superalloys. The demand for copper increases across all clean tech sectors, particularly for transmission infrastructure. Table 6 summarises the mineral demand for lithium, nickel, cobalt, and copper from the key focus clean technologies (batteries for EV and grid storage, solar PV, wind, and grid transmission) (IEA 2022c).

As can be seen in Figure 11, the identified clean technologies are expected to contribute a significant share of the total global lithium demand, followed by demand for cobalt and then nickel and copper.

> **The ratio of energy and non-energy demand of critical minerals will determine potential supply risks for clean energy sector.**

Figure 11 Share of mineral demand from focus clean technologies in total energy and non-energy demand



Source: IEA analysis

Table 7 Lithium demand (kt Li) across key clean technologies

Technology	STEPS		APS		NZE	
	2030	2050	2030	2050	2030	2050
Batteries (EV and Grid Storage)	240	490	368	1,089	628	1,178
EV batteries	*228*	*466*	*349*	*1,039*	*592*	*1,104*
Grid storage batteries	*12*	*25*	*19*	*50*	*37*	*74*
Solar PV	0	0	0	0	0	0
Wind	0	0	0	0	0	0
Grid transmission	0	0	0	0	0	0

Source: IEA and UC Davis analysis

Note: 1 Kt Li = 5.323 Kt LCE (lithium carbonate equivalent)

Across scenarios, the majority of the lithium demand (75–90 per cent) is expected to come from the focus clean technologies (solar, wind, batteries for EV and grid storage, and grid infrastructure). Nickel demand from the focus clean technologies is expected to cross 50 per cent in the APS and NZE scenarios by 2050, while copper demand is expected to range between 38–45 per cent in the APS and NZE scenarios by 2050. By 2050, cobalt demand from the key clean technologies is expected to cross 55 per cent of the total demand in both the APS and NZE scenarios. This provides a strong indication of the importance of these minerals in the development of key clean technologies. However, it should be noted that demand and supply cycles will depend on various factors, including commercial interests, market dynamics, regulatory and policy developments, and capital investments.

Lithium

Lithium demand for clean tech increases the fastest fuelled by an increase in the number of batteries for EVs and grid storage. In 2030, lithium demand at 240 Kt grows about five times from 2021 levels in STEPS and a little more than eight times in APS at 368 Kt. In 2050, the annual demand increases to twice that in NZE and close to 3x in APS. In all scenarios, 93–95 per cent of the lithium demand is expected to come from batteries for EV deployment. The rapid increase in the sales of EVs in the APS and NZE scenarios expected to contribute to the sharp rise in the demand for lithium.

> **Upto 95% of the lithium demand is expected to come from EV batteries.**

It should be noted that ambition to meet net-zero emissions accelerate deployment of EVs and grid battery storage from now and 2030 under APS and NZE. Thus, total annual demand for lithium from clean technologies accounts for about 75 per cent of the total lithium demand in 2030 in STEPS and about 88 per cent in 2030 under the NZE scenario. **By 2050, the EV and grid storage battery demand constitutes about 90 per cent of the total lithium demand across scenarios** (IEA 2022c)**.**

Nickel

The annual demand for nickel for batteries increases by about seven times under APS at 2140 Kt in 2030 and a little less than 11x under NZE scenario. The total demand for nickel is expected to go up to 3,394 kt under the NZE scenario compared to 3,364 kt in the APS scenario and 1641 kt in the STEPS scenario, in 2050. In all scenarios, of the five clean technologies identified, EV batteries constitute most of the demand for nickel, followed by wind.

It should be noted that of the total nickel demand estimated across all sectors for 2050, the above technologies constitute about 34 per cent of the demand in STEPS, 51 per cent in APS, and 55 per cent in NZE. **A significant portion of the demand is expected to come from other industrial applications such as steel, alloy making, and other uses.**

Cobalt

The total demand for cobalt is 291 kt for the year 2050 in the NZE scenario compared to 296 kt in the APS scenario and 146 kt in the STEPS scenario. **The reduced cobalt demand in 2050 in the NZE scenario is due to the assumption that there will be a shift in battery chemistries and more recycling, which will reduce the net cobalt requirement.** For the year 2030, an increase in cobalt demand is expected across all scenarios. **Of the identified technologies, all the demand for cobalt comes from battery demand for EV and grid storage, of which over 95 per cent is from EV batteries.**

Table 8 Nickel demand (kt) across key clean technologies

Technology	STEPS		APS		NZE	
	2030	2050	2030	2050	2030	2050
Batteries (EV and Grid Storage)	1,007	1,580	1,528	3,273	2,475	3,289
EV batteries	*988*	*1,580*	*1,498*	*3,273*	*2,414*	*3,289*
Grid storage batteries	*19*	*0*	*30*	*0*	*60*	*0*
Solar PV	0	0	0	1	1	1
Wind	50	61	73	91	137	104
Grid transmission	0	0	0	0	0	0

Source: IEA analysis

Table 9 Cobalt demand (kt) across key clean technologies

Technology	STEPS		APS		NZE	
	2030	2050	2030	2050	2030	2050
Batteries (EV and Grid Storage)	79	146	121	296	205	291
EV batteries	*74*	*146*	*113*	*296*	*188*	*291*
Grid storage batteries	*5*	*0*	*9*	*0*	*17*	*0*
Solar PV	0	0	0	0	0	0
Wind	0	0	0	0	0	0
Grid transmission	0	0	0	0	0	0

Source: IEA analysis

It should be noted that of the total cobalt demand across sectors, in the STEPS scenario, cobalt demand from the batteries sector is expected to constitute about 33 per cent in 2030 and 39 per cent in 2050, whereas, in the APS scenario, it is expected to constitute about 43 per cent in 2030 and 57 per cent in 2050. In the NZE scenario, cobalt demand from batteries is expected to constitute about 56 per cent of total demand in both 2030 and 2050. Significant cobalt demand is expected from other uses including superalloys.

Copper

Copper demand arising from the identified technologies in 2050 is expected to be about 17209 kt in the NZE scenario. In the STEPS scenario, copper demand is expected to reach about 10,572 kt by 2050, and in the APS scenario, it is expected to reach about 15,714 kt by 2050. **Grid transmission is the largest contributor to the demand for copper from the identified technologies, and it is estimated to contribute 66 per cent in STEPS and 57 per cent in NZE by 2050.** This is followed by batteries for EV and grid storage, which are expected to make up about a quarter of the demand by 2050 in the NZE scenario, followed by solar PV and wind. It should be noted that the total estimated copper demand for 2050 is around 36 kt (STEPS) and around 40 kt (APS and NZE). **Thus, the identified technologies are estimated to constitute about 40–43 per cent of the total demand by 2050 in the APS and NZE scenarios. Other major sectors of copper demand include construction and industrial equipment.**

Manganese

Manganese demand arising from battery technologies (EV + grid storage) in 2050 is expected to be about 1927 kt in the NZE scenario. In the STEPS scenario, manganese demand is expected to reach about 994 kt by 2050, and in the APS scenario, it is expected to reach about 1997 kt by 2050 (IEA 2022c).

Graphite

Demand estimates for graphite have only been made for battery manufacturing. In the STEPS scenario, the annual demand for graphite in 2030 is expected to reach around 1590 kt and then reduce to 1,077 kt by 2050 as chemistries improve. In the APS scenario, annual demand is expected to almost double by 2050, reaching 2486 kt, whereas, in the NZE scenario, it is expected to reach 2,726 kt as alternate chemistries such as solid state, sodium chloride, and others become commercially viable.

Table 10 Copper demand (kt) across key clean technologies

Technology	STEPS		APS		NZE	
	2030	2050	2030	2050	2030	2050
Batteries (EV and Grid Storage)	1,127	1,566	1,721	3,751	2,962	4,248
EV batteries	*1,044*	*1,346*	*1,592*	*3,307*	*2,704*	*3,583*
Grid storage batteries	*83*	*220*	*130*	*444*	*258*	*665*
Solar PV	907	1,262	1,194	1,873	1,976	1,880
Wind	661	762	842	1,203	1,611	1,303
Grid transmission	6,510	6,982	7,440	8,887	8,924	9,778

Source: IEA analysis

Table 11 Manganese demand (kt) across batteries

Technology	STEPS		APS		NZE	
	2030	2050	2030	2050	2030	2050
Batteries	152	994	231	1997	378	1927

Source: IEA analysis

Table 12 Graphite demand (kt) across batteries

Technology	STEPS		APS		NZE	
	2030	2050	2030	2050	2030	2050
Batteries	1,590	1,077	2,437	2,486	4,115	2,726

Source: IEA analysis

Table 13 Rare earth elements demand (kt) for wind

Technology	STEPS		APS		NZE	
	2030	2050	2030	2050	2030	2050
Wind	14	17	16	27	31	24

Source: IEA analysis

Rare earth elements

Demand estimates for REE have only been made for the wind sector. In 2050, the annual demand for REEs vary between 17-27 kt in 2050 in various scenarios.

6. Mineral value chain analysis

The mineral value chain is a complex process that involves various stages such as mining, exploration, processing, and distribution of minerals. The value chain is dynamic and constantly evolving with the development of new technologies and innovations.

6.1 Exploration of minerals

Mineral exploration is the process of searching for commercially viable minerals. It is the first stage in the mineral value chain. Common technologies used for the exploration of minerals are airborne surveys, borehole methods, electromagnetic methods, geochemical surveys, geological surveys, geophysical surveys, Geographic Information System (GIS), gravity methods, magnetic methods, remote sensing, radiometry, satellite imagery, and seismic methods (Okada 2022). These technologies may be used interchangeably based on cost-effectiveness, the availability of labour, and topographical ease (Okada 2022). Despite there being many existing methods, new exploration technologies are being developed to search better in uncertain conditions. The key novel exploration technologies are mentioned in Table 15.

6.2 Mining and extraction of minerals

Mining refers to the process of physically removing minerals from the earth's surface or from underground, while extraction refers to the process of obtaining the desired minerals from the ore or mineral deposit. In other words, mining is the physical act of digging, drilling, or blasting to access the mineral deposit, while extraction involves separating the desired minerals from the surrounding rock or ore (Sánchez and Hartlieb 2020). Mining is typically the second step in the mineral value chain, while extraction is a subsequent step in the process. Several techniques are used in current mineral mining and extraction practises, which are explained briefly in the Annexure. The mining techniques used vary depending on the type of mineral being extracted and the location of the deposit.

6.3 Processing of minerals

Mineral processing involves separating valuable minerals from the surrounding rock or brine and other impurities. Processing is typically the final stage in the mineral value chain and involves the refinement of minerals from their natural state into a usable form. This process typically involves a series of steps, including comminution, beneficiation, and refining (Shoppert, Karimova, and Zakharyan 2018). Each step is designed to separate the valuable minerals from the waste material and produce a high-quality product. Some of the processing techniques used for mining and extracting lithium, cobalt, nickel, copper, manganese, graphite, and REE are given in the Annexure.

Some of the commonly found forms of ores of critical minerals, along with the mining, extraction, and processing techniques used for obtaining these critical minerals for commercial use, are given in Table 14.

The mineral value chain is dynamic and constantly evolving with the development of new technologies and innovations.

Table 14 Current technologies adopted for mining, extraction, and processing of critical minerals

Critical Mineral	Mineralogy	Common ores	Mining and extraction techniques	Processing techniques
Lithium	Pyroxene, mica	Spodumene, lepidolite	Open pit, brine, underground, solvent extraction, acid, and in-situ leaching	Roasting, electrolysis, ion-exchange
Cobalt	Arsenide	Cobaltite, lateritic nickel ores	Open pit, underground, artisanal, small scale, In-situ, and by-product	Roasting, electro-winning, precipitation
Nickel	Silicates, sulphides	Pentlandite, laterite	Open pit, underground, cut and fill mining, heap leaching, solvent extraction	Pyrometallurgical, hydrometallurgical, precipitation
Copper	Sulphide, carbonate	Chalcopyrite, bornite, malachite	Open pit, underground, solvent extraction, and electrowinning	Smelting, Electrorefining
Manganese	Oxide, carbonate, silicate	Pyrolusite, rhodochrosite, braunite	Open pit, deep-sea, underground, leaching	Roasting, refining, electrolysis
Graphite	Native element	Natural graphite, flake graphite	Open pit, underground, dredging, floating pontoon	Froth flotation, gravity separation, and magnetic separation
Rare earths	Phosphate, carbonate	Monazite, bastnäsite, xenotime	Open pit, underground, heap leaching, In-situ leaching, solvent extraction	Ion exchange, electrometallurgy, floatation, magnetic separation, hydrometallurgy, calcination

Source: CEEW compilation from multiple sources – Siekierka et al. (2022), Khoo et al. (2017), Moats and Davenport (2014), Dehaine et al. (2021), Elliott et al. (2018),Fillo, Udall, and Ankeny (2022)), Keeling (2017), Ma et al. (2021), AFDB (2021), Haque et al. (2014).

6.4 Challenges in the mineral value chain

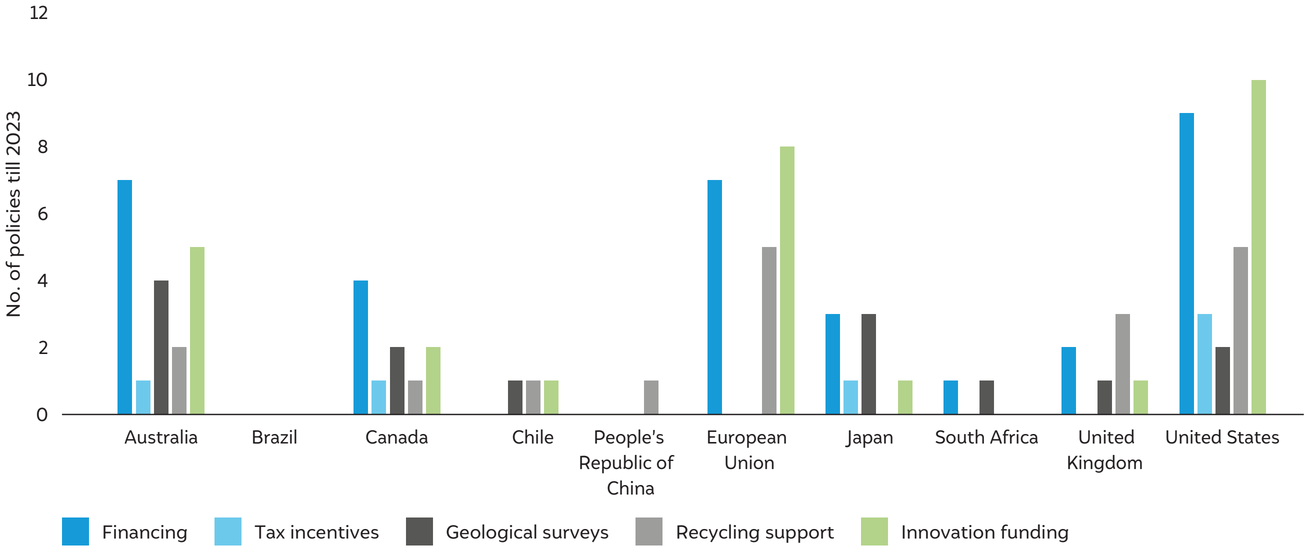
The exploration, mining, and processing of critical minerals faces several challenges that affect their economic viability and sustainability. One of the significant challenges in exploration is the lack of accurate data and information on the location, quality, and quantity of critical mineral deposits. This often results in increased exploration costs, delayed exploration timelines, and potential environmental impacts (Bontje and Duval 2022).

Mining critical minerals poses unique challenges due to their uneven geographical distribution and the technical difficulty in extracting them from the earth's crust. The high costs and significant time windows associated with developing an operational mine further exacerbate the challenge and make the mineral value chain more concentrated. Additionally, processing critical minerals is challenging, as it requires advanced technological solutions to extract, separate, and purify them. Some of the upcoming technologies in mineral mining, extraction, and processing are at the lab testing stage and/or are technologically constrained or IP protected. The policy landscape of different countries that have tried to diversify the mineral value chain is given in Figure 12 below.

Overall, addressing these challenges in exploring, mining, and processing is crucial for ensuring a secure and sustainable supply of critical minerals for the growing demands of modern society.

> **Some of the upcoming technologies in mineral mining, extraction, and processing are at the lab testing stage and/or are IP protected.**

Figure 12 Policy landscape of the major geographical players in critical mineral mining and processing



Source: CEEW adaptation from (IEA 2022b)

Table 15 Novel mineral exploration techniques

Exploration technique	Type of exploration technology	Description
Spatial associations using neural networks	Geological survey	Neural networks try to find spatial associations between known occurrences of minerals and predictive data sets. The analysis is used to identify areas with similar mineral characteristics. The process helps in identifying potential areas for mineral exploration.
Induced polarisation method	Magnetic methods	Through spectral-induced polarisation and resistivity measurements, mineral explorers can distinguish between mineralisation and the electromagnetic coupling effect. Meaningful anomalies associated with copper mineralisation are located by this method. This exploratory technique is also being tested for other minerals.
Airborne gravity gradiometry, proximal sensing, and remote sensing using unmanned aerial vehicles (drones)	Satellite imagery, airborne surveys, and remote sensing	Drones are being extensively used in a variety of exploration techniques. Drones are fitted with instruments to carry out airborne gravity gradiometry, which detects density anomalies caused by mineral deposits. This technology more effectively targets iron oxide, copper, and gold mineralisation and can be used in mountainous regions. Moreover, remote and proximal sensing is also carried out using drones. Accurate mineral maps can be generated using proximal and remote sensing techniques with per-pixel and sub-pixel image classifiers.
Airborne electromagnetic measurements using TEMPEST	Airborne surveys	TEMPEST is an airborne electromagnetic system operated from an aircraft. It investigates geological structures surrounding mineral deposits and covers large areas having diverse mineral deposits.
ASTER Maps	Satellite imagery	ASTER maps are one of the first continental-scale mineral maps that use satellite data to show information about rock and soil mineral components. They have been created from a 10-year archive of raw satellite data and provide a zoom comparable to Google Maps.

Source: Authors' adaptation from multiple sources, including Okada (2022) CSIRO (2023a), and CSIRO (2023b).

6.5 Role of technological innovations in diversifying the global critical mineral value chain

Technological innovations can play a crucial role in reducing the concentration of the critical minerals value chain in several ways:

- **Substitution**: Technological innovations can be used to identify and develop substitutes for critical minerals, reducing their demand in certain industries or applications. This can help to reduce the concentration of the critical minerals value chain and increase supply diversification.
- **Exploration**: Technology can be used to develop advanced exploration techniques that enable the discovery of new deposits of critical minerals. This can help to diversify the supply chain and reduce the concentration of the critical minerals value chain.
- **Efficient mining**: Technological innovations in mining can improve the efficiency of mining operations and reduce the amount of waste generated during the extraction process. This can help to reduce the concentration of the critical minerals value chain and also minimise the environmental impact of mining activities.
- **Recycling and reuse**: Technology can be used to develop efficient processes for the recycling and reuse of critical minerals from end-of-life products. By doing so, the demand for new mining activities can be reduced, thereby decreasing the concentration of the critical minerals value chain.
- **Digitalisation**: Digital technologies such as smart mining can be used to create a more transparent and traceable supply chain, from the mining site to the product (World Bank 2020).This can help to reduce the concentration of the critical minerals value chain by increasing supply chain visibility and promoting responsible sourcing practices.

Overall, technological innovations have the potential to reduce the concentration of the critica l minerals value chain by increasing supply diversity, promoting responsible sourcing practices, and improving the efficiency of mining operations.

Some of the technological innovations for the substitution of critical minerals have been described in the next section.

> Technological innovations could increase supply diversity, promote responsible sourcing practises and promote efficient mining operations.

6.6 Technological innovations in low-carbon technologies that can reduce mineral demand

This section lists some key innovations in battery, solar, EV, and wind systems that aim to reduce or remove critical minerals in their value chains.

Material innovations in battery technologies

- **Replacement of cobalt with other abundant metals in batteries:** Cobalt is used as a cathode material in certain lithium-ion batteries. Researchers are aiming to replace cobalt with relatively abundantly available metals such as nickel and manganese. Lithium-ion (nickel-manganese-cobalt – NMC) batteries have moved from having 60 per cent cobalt content in 622 battery types (60 per cent cobalt, 20 per cent nickel, and 20 per cent manganese in weight percentages) to 10 per cent cobalt in 811 battery types (80 per cent nickel, 10 per cent manganese, and 10 per cent cobalt in weight percentages) (Research Interfaces 2022). Future innovations in NMC batteries target overcoming issues such as reduced battery life due to the reaction of nickel atoms on the surface of the cathode with the cell's electrolyte and decreasing cobalt content, even lower than 10 per cent in the cathode material (Research Interfaces 2022).
- **Iron-based current collector foils as a replacement for copper in batteries:** Iron-based materials have high electrolyte resistance, excellent mechanical properties, and a wide electric potential window. As a result, they have the potential to replace copper as current collectors in batteries. Iron-based metal foils are expected to reduce the usage of copper in batteries and improve their performance and quality in the near future (Unno et al. 2019).
- **Rare-earth free negative electrodes in nickel metal hydride batteries:** The negative electrodes of nickel metal hydride (Ni/MH) batteries are made of REE. Developing rare earth–free negative electrode materials for Ni/MH batteries is desirable to reduce their dependence on critical REE. Recently, a titanium zirconium alloy was made with a formula that can replace rare earth–free negative electrodes in nickel metal hydride batteries (Şahin 2016).
- **Replacement of graphite with silicon in the anode of batteries:** Most lithium-ion batteries use graphite-based anodes with almost 10 times lower specific capacity (372 mAh/g, LiC_6) than silicon (4,212 mAh/g,

$Li_{22}Si_5$).[1] Such benefits make silicon one of the most promising materials to replace graphite. However, this high specific capacity of silicon comes with significant volume changes (more than 300 per cent as compared to the conventional battery volume). Also, when alloyed with lithium, such significant volume changes can cause severe cracking and disintegration of the electrode and lead to significant capacity loss (MIT 2022). Future research in this sector entails circumventing the deterioration of silicon-based anode materials during cycling. These recent developments greatly point towards advanced silicon-based anode materials in the near future (MIT 2022).

- **New battery technologies independent of critical minerals:** There is a significant push to develop new battery technologies that are critical mineral free. New battery technologies such as sodium sulphur, iron-air batteries, lithium-independent solid-state batteries, magnesium batteries, and zinc air batteries, which contain metal and oxygen-based electrodes, can potentially replace lithium-ion batteries in many applications (Kebede, et al. 2022). The metals used in these batteries, such as sodium, magnesium, and zinc, are abundantly available across geographies and show better performance than currently available battery technologies. However, many of these are still in various testing stages. The research community and battery manufacturers are working on identifying ways to scale them up.

Material innovations in solar cells

- **Reduction of silver in silicon wafer-based passive emitter rear contact (PERC) solar cells**: PERC cells use silver in the metallisation paste. Currently, the average silver consumption (mg/W) in standard M6 and M10 format PERC monofacial and bifacial cells is about 12 mg/W and is expected to reduce to 7.5 mg/W by 2032 (ISA 2022). Manufacturers are also exploring replacing silver with copper in the metallisation paste (Hutchins 2020), but challenges remain with identifying suitable equipment for copper plating and improving copper adhesion and the reliability of such modules (Lennon, Colwell, and Rodbell 2019) although Cu-plated metallisation promises significantly reduced costs for Si photovoltaics, its adoption in manufacturing has not gained the same traction.
- **Copper-free solar cells:** The copper-free solar cells include cadmium selenide, cadmium telluride, indium sulphide, tin oxide, and antimony selenide as photovoltaic materials. Recently, manufacturing processes have been developed to synthesise many of these using the spray pyrolysis technique, which can help in scaling up critical mineral-free solar PV (Vijayan, et al. 2022).

Material innovations in wind turbines

- **Replacement of permanent magnets and reducing REEs in wind turbines**: Considerable research is underway in the wind industry to reduce the use of critical REE in turbines. Some solutions involve reducing the dysprosium content to less than 1 per cent (Dodd 2018b), developing iron-based turbines (Greenspur 2022), and replacing magnets with high-temperature superconductors (King 2018; Nelson 2021).
- **Reducing neodymium in magnets in wind turbines:** Recent research and developments in making rare earth–free magnets for wind turbines has focused on reducing the amount of neodymium and substituting it with other metals. Cerium and terbium co-doped alloys are seen as potential replacements for neodymium in wind turbine magnets (Pavel, et al. 2017; Dodd 2018a).

Material innovations in electric vehicles

- **Rare earth-free motors in electric vehicles:** Most electric motors use magnets made of REE. Recent innovations have resulted in the use of wireless induction technology, in which power is transferred wirelessly through induction by a coil carrying alternating current (Hanley 2021).

> **Current innovations focus on reducing the usage of critical minerals in various clean technologies as well as replacing them with substitutes.**

1 Specific capacity is the the amount of electric charge the electrode material can deliver per gram of material (in milliampere hours/g or mAh/g).

Table 16 End-of-life recycling input rates (EoL RIR) of critical minerals for the clean energy transition in the EU

Mineral	EoL RIR (%)
Lithium	0
Cobalt	35
Dysprosium	0
Copper	17
Manganese	12
Nickel	34
Neodymium	1
Silicon	0
Silver	55
Titanium	19
Praseodymium	10

Source: European Commission (2021)

7. Role of circularity in meeting mineral demand

A circular economy promotes resource efficiency by helping meet the increased mineral demand, extending mineral use (through repair, reuse, and refurbishment of products), extracting minerals from waste products via recycling, and reintroducing them into use in manufacturing new products (EMF 2019). Hence, the circular use of minerals can reduce criticality by promoting efficient use and recovery from waste to provide an alternate supply chain.

7.1 How to assess the circularity of mineral supply chains

The circularity of a mineral is often measured by its end-of-life recycling input rate (EoL RIR). EoL RIR is an indicator of secondary mineral sources' contribution to the raw material supply. Several factors influence this indicator (European commission 2018).

- **Recyclability of the mineral**: The higher the recycling rate of a mineral in a product, the greater the share of secondary supplies.
- **Collection and waste channelisation**: Minerals used in products with difficult reverse logistics often contribute lesser to primary demand reduction.
- **Lifetime of the product**: The longer the life of the product, the lower the share of secondary supplies. Recycling of products with a long useful life will not match new mineral requirements, thereby reducing the contribution of recovered minerals in meeting primary demand.
- **Overall mineral consumption**: The higher the consumption of a mineral, the lower the share of secondary supplies. Such the mineral will be used in multiple industries with different levels of recyclability and useful life, and the share of recovered minerals in primary demand will be low.

It is important to note that EoL RIR is not a static parameter and will vary with the primary raw mineral supply of the subject country. For example, the following table summarises the European Commission's assessment of the RIR of critical minerals in clean energy. It shows that the recovery of minerals from waste recycling makes a negligible contribution to meeting the primary mineral demand. Similar assessments by other countries would provide a more realistic assessment of the contribution of waste recycling to the primary raw mineral supply.

7.2 Opportunities for circular economy strategies in reducing mineral criticality

The world is staring at an impending influx of clean energy waste: about 1.3 TWh of batteries will reach end of first useful life by 2040 (IEA 2022b), 60 to 78 million tonnes of solar PV module waste will be generated by 2050 (IEA-PVPS 2018) and 43 million tonnes of waste wind turbine blades will be produced by 2050 (Liu and Barlow 2017). However, only a few jurisdictions have legislative frameworks to mandate the efficient collection, recycling, and disposal of clean energy waste. The European Union is an early mover with dedicated waste management regulations for batteries (European Commission 2019) and solar PV modules (European Commission 2012). India has also issued waste management regulations for both technologies (MoEFCC 2022). The US does not have a national regulation for either of these technologies, but states such as California, New Jersey, Hawaii, North Carolina, and Washington have regional regulations for managing solar PV module waste (US EPA 2022).

While mineral recovery from recycling does provide a direct route to reduce mineral criticality, other strategies are also available. Criticality can also be managed at the product design stage by extending products' life. For instance, by 2040, recycling and reusing batteries can reduce the primary supply of battery minerals such as cobalt, nickel, and lithium by up to 12, 7, and 5 per cent, respectively (IEA 2022b).The following sections discuss some examples of how various stages of the circular economy can address mineral criticality in clean energy technologies

Reducing criticality via end-of-life recycling

- **Batteries**: Among all the discussed clean energy technologies, battery recycling is the most advanced from the technological, efficiency, and demonstration perspectives. The impetus comes from the presence of several critical minerals in waste batteries like lithium ion.

  Technology: Lithium-ion battery recycling is mostly done via a combination of thermal, pyrometallurgic, and hydrometallurgical processes (Sojka, Pan, and Billmann 2020) First, a discharged, disassembled battery is pre-treated via mechanical or pyrolysis treatment to recover steel, copper, and aluminium. The remaining minerals (copper, nickel, and cobalt) are recovered using hydrometallurgic and pyrometallurgical methods.

- **Solar PV modules**: Recycling of solar PV modules is still at a nascent stage. As the modules have a long useful life, the research, development, and demonstration of recycling processes are yet to match the scale of battery recycling.

  Technology: Solar modules are also recycled via a combination of mechanical, chemical, and thermal processes (IEA-PVPS 2018). There are three main steps in solar module recycling: disassembly of the module to recover the aluminium frame and junction box (not applicable to thin-film modules), delamination to remove the encapsulant, glass, and backsheet, and metal recovery to recover silicon, silver, cadmium, tellurium, etc. as applicable. Currently, the recycling of bulk materials (aluminium and glass) is more common than metallic minerals. However, ongoing research is focused on achieving complete recovery of minerals.

- **Wind turbines**: Wind turbines have five major components: foundation, tower, turbine blades, rotor hub, and nacelle. Most of the critical minerals (REE like neodymium, dysprosium, and praseodymium) are present in the permanent magnets of the turbines used in direct-drive permanent magnet synchronous generators, the dominant type used in offshore installations (IEA 2022b). The magnets, steel tower, and rotor hub are easy to recycle while the blades and nacelle are more challenging. Blades and nacelle are composite materials made up of fibreglass, carbon fibre, and polymeric resin (Jacoby 2022). Some of the commonly used resins are thermosetting, which further strengthen when subjected to high temperatures.

  Technology: The permanent magnet is the most useful part of wind turbine waste due to the presence of REE. A recent study uses rapid solidification, a melt spinning process, to recycle all the elements present in permanent magnets (Bertrand 2015). There are no efficient recycling processes available for blades. Some of the current waste management processes involve shredding blades and using them in cement manufacturing.

8. Recommendations for G20

Priority 1 – A shared vision on critical minerals holds the key to increased mineral supply

Action 1: Institutionalising periodic tracking and assessment of the critical mineral value chain: Critical mineral value chain assessments are currently being carried out by countries and individual institutions across the world. To meet the global increasing mineral demand, countries need to come together to assess and track the critical mineral value chain. As part of this process, compendiums, reports, and technical papers can be prepared, which will provide a stocktake of the current demand and supply of critical minerals. In addition, these research reports can also provide a blueprint for commercialising new innovations. An annual conference on critical minerals may also be institutionalised to ensure the continuity of discussions.

> A shared vision on critical minerals as well as the infusion of LiFE principles would enhance global mineral security.

Action 2: Diffusion of technological innovations and new geographies for the exploration and production of minerals: Minerals are found in different forms across the world. Researchers are developing new environmentally friendly methods and technologies to explore and mine these minerals. It is recommended that G20 countries increase budgetary spending towards developing and deploying new technologies and encourage cross-country collaboration. Additionally, developing mines have extended lead times (upto 10 years). Against the backdrop of increasing mineral demand, multinational banks should agree to invest in new mining activities related to critical minerals. This will help meet the demand in the long term.

Action 3: Build a common approach towards a strategic stockpile of critical minerals: Global institutions in the past have been created (for example, the IEA with respect to oil security) to develop safety nets for reliable supplies, including strategic stockpiling of natural resources to weather short-term supply disruptions. These institutions help countries conduct regular market assessments, periodic stress tests, and voluntary emergency response exercises to evaluate weak points and prepare adequate measures. Critical minerals can be equated with a similar status given the sensitive nature of the supply chain. Such programmes need to be carefully designed, based on a detailed review of potential vulnerabilities, to avoid any unintended consequences.

Priority 2: Infusing LiFE principles to enhance global mineral security through reduce reuse, and recycle efforts

Action 1: Reducing material intensity by scaling up global R&D and improving procurement practices: Strategic and environmental considerations require that all efforts be taken to reduce the share of critical minerals in the technologies that will define the world's energy future. G20 countries should agree to develop R&D programmes that either improve existing technologies or prioritise the development of alternative technologies that would be more material-efficient and environmentally friendly. The G20 should actively aim to build a network around existing and upcoming clean energy technology–related R&D groups and ensure the learnings from these research flow seamlessly to G20 countries. The group can jointly agree to provide fiscal and monetary support to these efforts so that the research outputs are focused and shared globally. Additionally, transitioning technologies from R&D to commercial scale deployment requires certainty in the form of volume and continuity of procurement. The G20 as a whole is a significant market, which can help support this transition while possibly reducing costs – a step that can benefit poorer, non-member countries too going forward.

Action 2: Infusing circularity in mineral value chain: Reusing minerals and materials from existing clean energy technologies will reduce the demand for new minerals and ease the supply chain. Additionally, local technology hubs can also be established where mineral recovery industries can be developed and new jobs created. However, mineral recovery technologies and their associated IP is still concentrated in a few centres. Enabling regional and local ecosystems to recover through global mandates that encourage local recovery would pave the way for equitable access to recovered minerals.

9. Conclusions/key takeaways

Globally, the rapid adoption of low-carbon technologies is needed at an enormous scale to ensure sustainable economic growth. However, a major challenge to such a scale-up is significant quantity of minerals required to manufacture these technologies. Current production of many of these minerals will not be sufficient to meet predicted global demand. Expanding access to these minerals, and reducing demand where possible, will thus be key to securing the world's sustainable future.

Some minerals are considered critical by countries due to vulnerabilities in their supply chains and the quantum of present and future demand. Certain minerals, such as cobalt, copper, graphite, lithium, manganese, nickel and REEs are considered critical from the context of manufacturing low-carbon technologies. These minerals are geographically concentrated in their production, and low-carbon technologies are expected to make up a sizeable portion of their total demand in the coming years. In many countries, the exploration of these minerals is still at a very nascent stage. Expanding exploration and mine development responsibly will help ensure production of minerals scales up to meet demand, and that it is distributed over many more geographies. New technologies are also being developed that could reduce the need for these critical minerals in low-carbon technologies. By deploying such substitutes and supporting the circular economy of these technologies, the criticality of these minerals can be reduced considerably.

Countries will need to develop a shared vision on critical minerals to secure supply. This will involve periodically tracking and assessment of the critical mineral value chain, as well as supporting the diffusion of novel technologies and strategic global stockpiling. Simultaneously, countries should encourage reusing and recycling of low-carbon technologies and reducing technology mineral intensity based on LiFE principles. This will be crucial to secure the future low-carbon transition.

Annexure

Annexure 1 Common techniques for mineral mining and extraction

- **Open-pit mining**: Open-pit mining involves the excavation of large open pits or quarries to extract minerals from the ground. This method is typically used for minerals that are near the surface and can be extracted using heavy machinery such as bulldozers, excavators, and trucks.
- **Underground mining**: Underground mining involves the excavation of tunnels and shafts to access minerals that are located deep beneath the earth's surface. This method is typically used to mine minerals that are located at greater depths, such as coal, gold, and copper.
- **Placer mining**: Placer mining involves the extraction of minerals from riverbeds and alluvial deposits using water and gravity. This method is typically used for minerals such as gold, tin, and diamonds.
- **Solution mining**: Solution mining involves injecting a solvent, such as water or acid, into a deposit to dissolve the minerals and extract them from the ground. This method is typically used for minerals such as salt, potash, and uranium.
- **In-situ leaching**: In-situ leaching involves injecting a solution into a deposit to dissolve the minerals and extract them from the ground without excavating the ore. This method is typically used for minerals such as uranium and copper.
- **Mountaintop removal mining**: Mountaintop removal mining involves the use of explosives to remove the top of a mountain and extract minerals from the exposed coal seams. This method is controversial due to the environmental impacts on the surrounding ecosystem and communities.
- **Heap leaching**: Heap leaching can be used for some rare earth deposits, where the ore is stacked in a heap and a solution is applied to extract the minerals.
- **Solvent extraction**: Solvent extraction is a common technique used to extract REE from the ore. This involves dissolving the minerals in a solution and then using a chemical solvent to extract the REE from the solution.

Annexure 2 Common techniques for mineral processing

Several common mineral processing techniques are used in the mining industry. These techniques are used to extract and refine valuable minerals from the ore or mineral deposit.

- **Comminution**: This is the process of reducing the size of the ore or mineral deposit through crushing and grinding. The process aims to increase the surface area of the mineral particles, making it easier to extract valuable minerals.
- **Gravity separation**: This technique involves using the difference in density between the mineral and the surrounding rock to separate the two. This technique is commonly used for gold, tin, and tungsten.
- **Flotation**: This technique involves adding chemicals to the ore or mineral deposit to make valuable minerals hydrophobic (repel water) and unwanted minerals hydrophilic (attract water). The hydrophobic minerals are then separated from the hydrophilic minerals using air bubbles.
- **Magnetic separation**: This technique uses magnetic forces to separate magnetic minerals from non-magnetic minerals. This technique is commonly used for iron ore and magnetite.
- **Leaching**: This technique involves using chemicals to dissolve valuable minerals from the ore or mineral deposit. The resulting solution is then processed to recover the valuable minerals.
- **Electrostatic separation**: This technique involves using electric charges to separate minerals based on their conductivity. This technique is commonly used for separating conductive minerals such as copper and aluminium from non-conductive minerals such as quartz.
- **Hydrometallurgy**: This technique involves using water-based solutions to extract valuable minerals from the ore or mineral deposit. This technique is commonly used for processing copper, nickel, and cobalt ores.
- **Pyrometallurgy**: This is a high-temperature metallurgical technique used to extract metals from ores or raw materials. The process involves heating the raw material in the presence of a reducing agent to remove unwanted impurities and produce a pure metal.

Overall, these mineral processing techniques are essential in extracting and refining valuable minerals from the earth's crust and are critical for many industries that rely on these minerals for their products and processes.

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