CRITICAL TRANSITIONS

Circularity, equity, and responsibility in the quest for energy transition minerals

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Acronyms

APS	announced pledges scenario (IEA)
BAT	best available technology
CBD	Convention on Biological Diversity
CMETC	critical minerals exploration tax credit
CODES	the Coalition for Digital Environmental Sustainability
CSP	Concentrated solar power
DRC	Democratic Republic of the Congo
EJ	exajoule (a unit of energy: 1EJ=1018 joules)
EOL	end of life
EPR	extended producer responsibility
ERA	Environmental risk assessment issues
EU	European Union
EV	electric vehicle
FCEV	fuel cell electric vehicle
G7	The Group of Seven
G20	The Group of Twenty
GBF	Kunming-Montreal Global Biodiversity Framework
GDP	Gross Domestic Product
GHG	greenhouse gas
ICMM	International Council on Metals and Mining
IEA	International Energy Agency
ILO	International Labour Organization
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRMA	Initiative for Responsible Mining Assurance
IRP	International Resource Panel
LIC	Low-Income country
LMIC	Lower Middle-Income Country
MW	megawatt (1,000 kilowatts)
NBSAP	National Biodiversity Strategies and Action Plans
NZE	net zero emissions by 2050 scenario (IEA)
OECD	Organization for Economic Co-Operation and Development
PDAC	Prospectors and Developers Association of Canada
PGM	platinum group minerals
PV	photovoltaic
REE	Rare earth elements
RMF	Responsible Mining Foundation
R&D	Research and development
SDG	Sustainable Development Goal
STEPS	stated policies scenario (IEA)
TCFD	Taskforce on Climate-related Financial Disclosures
TNFD	Taskforce on Nature-related Financial Disclosures
TSM	Towards Sustainable Mining
TWh	terawatt hour
UNEA	United Nations Environment Assembly
UNEP	United Nations Environment Programme
UNGA	United Nations General Assembly
WEF	World Economic Forum
WHO	World Health Organization
WWF	World Wide Fund for Nature

Glossary

Business-as-usual (BAU) scenario – is defined as the 'no intervention' scenario; in other words, BAU assumes that the current policy framework, market dynamics, cultural norms and consumer behaviours do not change.

Circular economy – is where products and materials are designed in such a way that they can be reused, remanufactured, recycled or recovered and thus maintained in the economy for as long as possible, along with the resources of which they are made, and the generation of waste, especially hazardous waste, is avoided or minimized and greenhouse gas emissions are prevented or reduced, can contribute significantly to sustainable consumption and production (UNEP/EA.4/Res.1).

Closed material loops – occur when a material or product can be recovered and reused or recycled indefinitely for the same application for which it originally had, without a loss in quality and with zero waste (Toledano, Brauch and Arnold 2023).

Digital economy – The global network of economic and social activities that are enabled by digital technologies, such as the internet, mobile technology and the internet of things

Energy transition – is the move away from fossil fuels and towards renewable energies as a critical part of reduce greenhouse gas emissions and avoiding dangerous climate change. The energy transition itself is commonly described as either the 'green transition' or the 'clean transition'. Both concepts are commonly employed to refer to a transition to energy generation sources that do not actively contribute to climate change, for instance because they are carbon neutral or very low carbon emitters. But 'clean energy' as commonly employed includes nuclear generation, whereas 'green energy' seeks to distance itself from the toxic waste products associated with nuclear energy.

Extended producer responsibility – is where a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle to encourage reuse or recycling (Toledano, Bauch and Arnold 2023).

Life cycle approach - identifies both opportunities and risks through the entire life cycle of a product or technology, all the way from raw materials to disposal (UNEP 2004).

Nature positive – nature positive outcomes entail the protection and restoration of natural processes, ecosystems and species (Graham 2022).

Net zero – means cutting greenhouse gases to as close to zero as possible, with any remaining emissions re-absorbed from the atmosphere, by oceans and forests for instance (UN net-zero coalition).

Open material loops – mix materials of different sources and levels of quality, without traceability associated with the materials. As such, they are associated with the downgrading of material quality and the rejection of some materials for being of too low quality to be used (Toledano, Bauch and Arnold 2023).

Primary energy demand – refers to the total amount of energy required to meet the energy needs of a particular region, country, or sector. It represents the sum of energy consumed before any transformation (i.e. into electricity) takes place. It differs from final energy consumption which refers to the amount of energy reaching end users once accounting for losses from conversion and transmission.

Process circularity – refers to reducing emissions and minimizing, reusing and ultimately eliminating waste at mine sites and metal industries (Toledano, Bauch and Arnold, 2023).

Product circularity - refers to repairing, reusing and remanufacturing equipment, and harvesting and recycling metals indefinitely through product design and collection processes (Toledano, Bauch and Arnold 2023).

Responsible mining – Mining is extracting finite resources, so it can never, by definition, be 'sustainable'. However, it can be 'responsible' where it respects human rights, delivers safe conditions for personnel and communities, and minimises environmental impacts.

Systems change - captures the idea of addressing the causes, rather than the symptoms of a societal issue by taking a holistic (or 'systemic') view. Systemic change is generally understood to require adjustments or transformations in policies, practices, power dynamics, social norms or mindsets. It often involves a diverse set of players and can take place on a local, national or global level. Systems change requires modifications in many of the system structures, such as the mindset or the paradigm that creates the system or the system's goals or rules (Meadows 1999).

Transition minerals – are understood here as the 26 minerals and metals that are necessary to equip the energy transition to shift the production, storage, transmission, and use of energy from fossil fuels to renewable sources. The list includes aluminium, boron, cadmium, chromium, cobalt, copper, gallium, germanium, gold, graphite, indium, lead, lithium, manganese, molybdenum, nickel, platinum group minerals, rare earth elements, silicon, silver, tellurium, tin, titanium, vanadium and zinc.

Waste hierarchy – is a concept that outlines a preferred order of actions to minimize and manage wase. It consists of five levels: prevention, minimization, recycling, recovery and disposal.

Contents

Executive Summary

Faced with the urgent and growing threat of climate instability, the global community must take unprecedented action to transform a global energy and transport system that is still 80 per cent powered by fossil fuels. Pursuing business-as-usual by continuing to extract and burn billions of tons of fossil fuels every year is not a viable option. Put simply, the energy transition is a critical transition.

The good news is that the world is on the cusp of an energy revolution. A range of proven and cost-effective renewable energy technologies that harness the power of wind, water, wave, solar and geothermal energy are being deployed at pace. Renewable energy production capacity increased five-fold between 2011 and 2023. The efficiency of renewable electricity generation has increased dramatically in recent decades, making renewable energies a viable primary energy source in many countries.

There is a race to roll out this technology and reach 'net zero' - the point where the global economy produces no more greenhouse gases than the planet can absorb. Yet, this must be done in a way that includes the nearly three quarters of a billion people who currently lack access to electricity. We also must be sure to not leave developing and resource-rich countries behind in the development of renewable energy systems. Managing this equity is critical for a transition to a new renewable energy system to be successful – as evidenced by the strong emphasis on justice, sustainability and equity in the principles issued by UN Secretary General's Panel on Critical Energy Transition Minerals in September 2024.

The energy transition is mineral hungry. Clean energy technologies require large quantities of minerals to build electricity grids, produce solar panels, construct batteries and so on. Roughly two dozen minerals are essential to clean energy technologies. Equipping the world for net zero by 2050 implies a six-fold increase in production of these minerals from 2022 levels. This will generate large environmental and social footprints with little gain in shared benefits if the materials necessary for the transition are mined, processed and disposed of in an irresponsible manner. Given that many of the same minerals are used in the smart phones and data centres that power the new digital economy, these materials are clearly increasingly important to economies in the twenty-first century.

The speed and scale of the energy transition is uneven: it depends on access to the critical energy transition minerals in the right places at the right time. The supply chains of energy transition minerals are complex, fragile and often dominated by a limited range of countries and companies. This makes them vulnerable to political pressure and economic shocks. The speed and scale of the energy transition is uneven, it depends on access to critical energy transition minerals and relevant technologies and access to benefits of the energy transition.

The demand for minerals for the energy transition presents an opportunity to achieve the 2030 Agenda. This is further emphasised in the fourth principle of the United Nations (UN) Secretary General's Panel on Critical Energy Transition Minerals which emphasises the importance of using benefit sharing, value addition and economic diversification to foster development. Lower income countries, which often have a wealth of energy transition minerals, have yet to fully participate in the current resource boom. Enabling developing countries that have large sources of minerals to add value to their minerals (through processing the materials and developing clean energy products) and supporting the equitable benefit sharing of the proceeds of mining is key to finance and support the development agendas of these countries.

Despite the heavy environmental and social footprint of mining, investors and companies are putting pressure on governments to loosen permitting procedures for new mine sites both onshore and in the depths of the ocean. The past few years have seen a 'gold rush' over energy transition mineral reserves. However, rushing headlong into ever increasing mining of virgin terrain is a very risky strategy that can negatively impact the wellbeing of nearby communities and destroy biodiversity. Deep sea mining in particular carries many uncertainties and requires the utmost caution before proceeding.

Greater efficiency and circularity could reduce the cumulative need for new energy transition minerals by 2050. This would save money, minimise supply risks and avoid causing serious environmental damage. Responsible mining for the remaining mineral requirements is vital for ensuring that the social and environmental impacts of mining do not damage surrounding communities. The UN Secretary General's Panel on Critical Energy Transition Minerals has highlighted the need for increased material efficiency and circularity in their fifth "Actionable Recommendation".

Concerted action by all stakeholders is needed to make the energy transition sustainable. Public and private stakeholders need to work together to foster equitable, innovative and trusted mineral supply chains. As put forth in this working paper, this will require action in four key areas. First, standards and regulations need to drive investment and create markets for more efficient and circular innovation, processes and products. Second, public incentives for greater efficiency and circularity must be aligned to support and grow those markets. Third, accountability and transparency have to be promoted along the supply chain to ensure equitable sharing of benefits, particularly for developing countries producing energy transition materials. Finally, international cooperation and national management of energy transition mineral supply chains must be improved to ensure that sustainability is maximised throughout.

Eight 'R's' can guide this action. Collectively, the international community, national governments, industry and investors need to work together. We should **rethink** systems of mobility, housing and industry to meet the same human needs with fewer minerals. We need to **reduce** the meteoric demand for energy transition minerals through improvements to material and energy efficiency. We must **replace** energy transition minerals for lower impact substitutes where possible. We have to **reuse** products in second and third lives while finding ways to retain the minerals in use for longer. We must **recover** minerals more effectively from production processes and legacy tailings sites and **recycle** them into new products. It is vital that those minerals that do need to be extracted, are extracted in a responsible way, adhering to ambitious environmental, social and governance standards. Equity in access to energy transition minerals and also in sharing in the benefits granted by the energy transition must be a guiding principle.

This UNEP working paper contributes to the furtherance of Principle 2 and the operationalization of Actionable Recommendation 5 of the UN SG's Panel on Critical Energy Transition Minerals launched in early September 2024. AR5 seeks to enhance material efficiency and circularity to balance mineral consumption with sustainable supply and reduce environmental risks and impacts of resourcing the energy transition. It introduces key questions on equity and the sustainable energy transition, which UNEP will continue to address and research in future publications.

[1] Although the digital transition is one contributing driver of the growing demand for energy transition minerals, it is not a major focus of this working paper.

I. Mining and the energy transition

This working paper gets to the heart of a complex challenge facing humanity. The world needs vast quantities of minerals to leave the fossil fuel age behind, but these must be produced in a manner that is neither socially nor environmentally damaging. And, it needs to be done quickly.

Unless the minerals used to equip the energy transition are extracted and managed responsibly and efficiently, and the benefits shared equitably across producer and consumer countries, the transition could have negative consequences on communities, development and the environment. Under a business-as-usual scenario, more ambitious climate goals, imply more intensive mineral needs (Ekins et al. Forthcoming). This paper outlines a vision for a future where more efficient, circular and responsible use of energy transition minerals equips the green transition, while concurrently meeting climate, biodiversity and pollution goals.

This paper builds on the research of the UNEP-hosted International Resource Panel, the International Energy Agency and the International Renewable Energy Agency, as well as extensive intergovernmental consultations on the environmental aspects of minerals and metals management in 2023 mandated by a resolution passed at the fifth session of the United Nations Environment Assembly. The paper does not aim to provide a comprehensive analysis of the many complexities surrounding mining, minerals value chains and the energy transition. Instead, it strives to consolidate current knowledge and key questions on circular economy and highlight some of the core environmental and social challenges that emerge across the life cycle of 26 energy transition minerals. This effort serves as a conceptual foundation for UNEP's circular economy approach to mining.

The recommendations at the conclusion of this document outline an initial framework called the "Eight R's", designed to integrate efficiency, circularity and responsibility across the life cycle of minerals essential for the energy transition. They also explore some of the actions that governments and industry (including the mining industry, product manufacturers and investors) can take to shift markets towards greater efficiency and circularity by taking advantage of opportunities and reducing risks. UNEP is actively conducting further research into the different approaches to circularity, particularly exploring issues and options of enhanced equity that emerge from this framework. These topics will be further addressed and quantitatively analysed in future UNEP publications.

Bidding goodbye to the fossil age?

If the world is to reach net zero by 2050 and avert dangerous climate instability, the world needs to revolutionise the way that energy is produced and used. Six features of the modern energy system shape this challenge:

1/. Humanity is still heavily reliant on fossil fuels: Three quarters of total global primary energy consumption in 2022 was from fossil fuels (International Energy Agency [IEA] 2022a). The world is still very much stuck in the fossil fuel age. Leaving it requires a rapid deployment of clean energy at all scales around the world. Doing that means governments also need to re-equip and upgrade the world's energy infrastructure, particularly the grid systems that transport electricity. Energy storage must be improved as well.

2/. Hundreds of millions of people are denied the benefits of modern energy: Access to energy is still deeply unequal across the globe. In 2022, 754 million people were living entirely without access to electricity and 2.4 billion people lacked access to clean cooking fuels (IEA 2022a). Between 2021 and 2022, the number of people living without access to electricity actually grew by six million people, breaking a decades-long downward trend (IEA 2022a). Women, particularly in developing countries, often lack access to reliable and clean energy, affecting their quality of life and economic opportunities.[2] This means that the world needs to decarbonise its energy system, while simultaneously extending energy access to hundreds of millions of people. It also means ensuring that countries and communities are not left behind in the goal of sustainable energy for all. This means that mechanisms must be created that safeguard developing countries' affordable access to the energy transition minerals that are needed for them to make their own energy transition.

3/. Demand for energy is rising: Primary energy demand jumped by 5.8 per cent between 2020 and 2021 as the world recovered from the COVID-19 pandemic. It continued rising (by 1.1 per cent) between 2021 and 2022 (Energy Institute 2023). This means that the energy transition must cater for increased demand. Climate change itself is adding to the challenge by, among other things, increasing the demand for cooling, which already accounts for 20 per cent of the total electricity used in buildings today. Without action on increased energy efficiency, demand for cooling alone could triple by 2050 (IEA 2018; United Nations Environment Programme [UNEP] 2023a).

4/. Sources of energy are changing: The balance of the world's energy system is changing. Electricity generation currently makes up around a third of most countries' primary energy demand (the remainder includes fuel for vehicles and heating as well as losses during electricity generation and transmission). Over time the proportion of primary energy demand devoted to electricity production will rise as more of the economy uses electricity rather than fossil fuels. Indeed, this is inevitable as electric vehicles progressively replace vehicles that use internal combustion engines and as electricity-powered heat pumps replace oil-fired home heating systems (IEA 2022a). In fact, a net zero economy would require electricity demand and supply to almost quadruple, from 28 million terawatt hours (TWh) in 2022 to 100 million TWh in 2050 (Energy Transitions Commission [ETC] 2023a). However, while electricity generation from renewables would need to grow in a net zero scenario, it will be more efficient to produce that energy than it is to produce energy from fossil fuels (Eyre 2023).

5/. Renewables are coming on-stream: The transition is rapidly approaching. Countries representing more than 70 per cent of global GDP and global emissions have committed to net-zero emissions by or before 2050. This implies that there will be a massive increase in the deployment of renewable energies (IEA 2022a). At least 174 countries have set targets to increase their share of renewable power, including 37 countries that have set a 100 per cent renewable target (REN21 2023). Renewable energy has also become the most affordable form of electricity generation across much of the world over the past decade (International Renewable Energy Agency [IRENA] 2023). This is all the more impressive when it is considered that the affordability of this energy is calculated before even considering the benefits to human health and the environment from reduced pollution. Furthermore, 83 per cent of newly added capacity for electricity generation in 2022 was from renewable energies (IRENA 2023). As the cost of renewable energy comes down, the pace of its deployment has accelerated. Roughly 30 per cent of the world's electricity supply came from renewable energies by the end of 2022 (REN21 2023).

6/. But there is still a huge amount to do: The speed at which renewable technologies are being deployed needs to triple for net zero to be reached by 2050 (IRENA 2023). Reaching net zero means electrifying as much as possible, decarbonizing the electricity supply and using green hydrogen and bioenergy wherever direct electricity use is not feasible. The Energy Transitions Commission estimates that wind power needs to increase 15 times (from 1 TW to 14-15 TW), solar power by twenty-five times (1.2 TW to 26-34 TW) and the production of green hydrogen needs to increase by at least 500 times (from

[2] There is a clear and important intersection between energy access and gender equality. Women and children are often disproportionately affected by lack of energy access because large amounts of their time and labour must typically go towards meeting daily needs (for example gathering biomass for cooking or manually processing grain or other food in the absence of machines) (United Nations Department of Economic and Social Affairs [UNDESA] 2018).

[3] Strictly speaking, silicon in its pure form is considered an element not a mineral, but it is mined in mineral form.

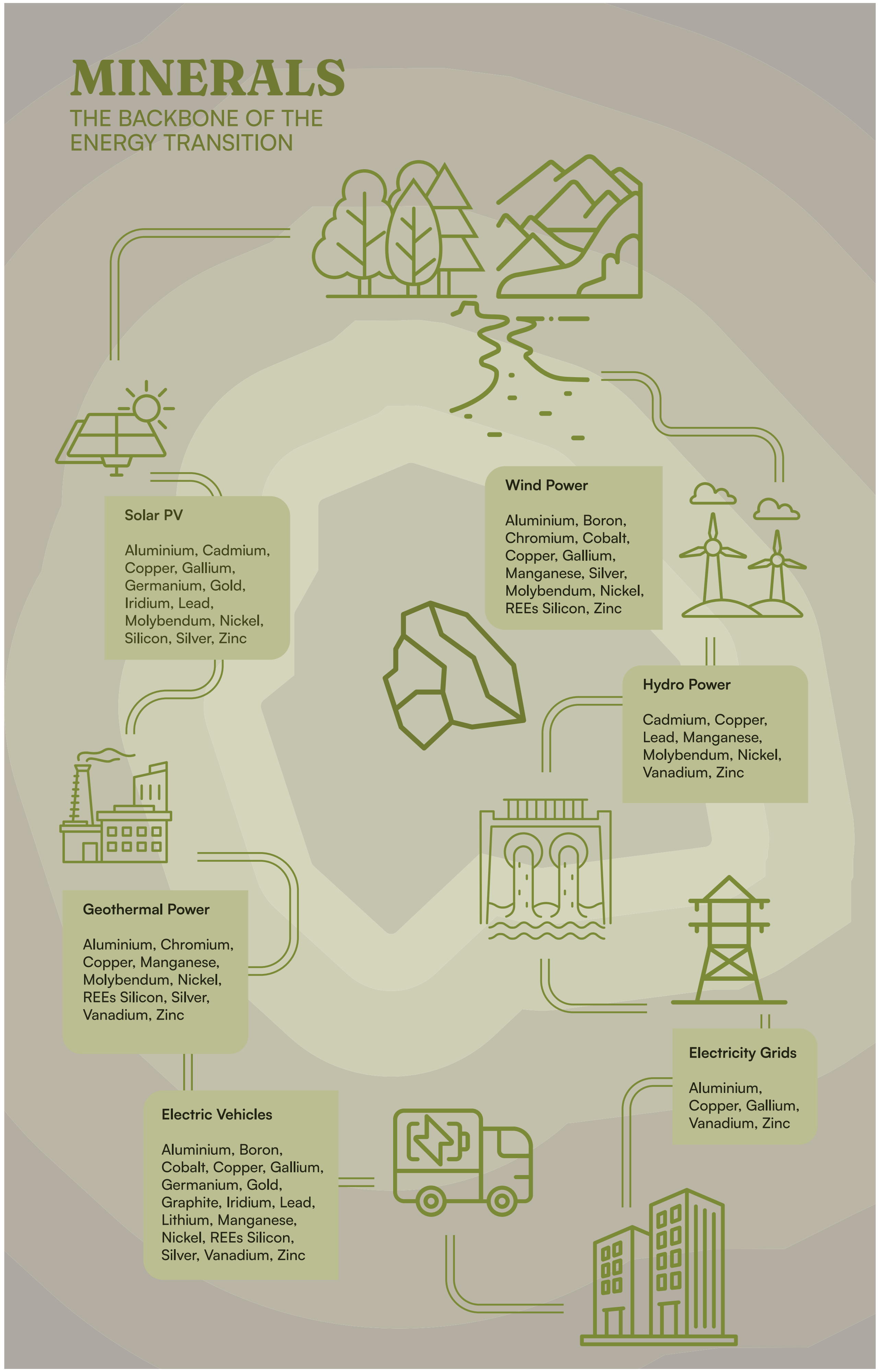


Figure 1: Many different minerals are needed to make a wind turbine, an electric vehicle, or a solar panel.

less than one million tons now to between 500 and 800 million tons) (ETC 2023a). The number of electric cars on the road needs to jump from around 25 million now to 1 billion by 2050 (Turner 2023). Further, there is also a need to encourage public transportation and the use of electric vehicles for public transport. Getting electricity to the people who need it means that power transmission grids need to grow from 70 million kilometres to around 200 million kilometres (ETC 2023a).

Box 1: Defining energy transition minerals

The UN Secretary General's Working Group on Transforming Extractive Industries for Sustainable Development defines critical energy transition minerals to refer to mineral commodities that are necessary for the construction, production and storage of renewable energy. Defining what should be on a list of energy transition minerals is complex. Often labelled 'critical minerals', there is no universally accepted list (IRENA 2023). Many different countries and regions have come up with their own lists of 'critical' minerals. Unfortunately, the factors used in determining their criticality are both highly subjective and location-specific. This report has elected to focus on a list of 26 minerals found on the IEA list (2022a) combined with that of Eurométaux, the European industry association of non-ferrous metals producers and recyclers (2022).[3] Ultimately, the key criterion for inclusion on the list was whether the mineral is key to the energy transition due to its use in transportation or energy generation, transmission or storage technologies. In summary, the list is focused on the minerals that are essential for the functioning of renewable energy technologies and which have supply chains that may be vulnerable to disruption.

	Wind	Solar PV	CSP	Geother-mal	Hydro	Bioenergy	Hydrogen	Electricity Grids	EVs	Battery Storage
Alumimium	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
Boron	◆								◆	
Cadmium		◆								◆
Chromium	◆		◆	◆	◆		◆			
Cobalt	◆		◆			◆	◆		◆	◆
Copper	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
Gallium	◆	◆						◆	◆	
Germanium		◆							◆	
Gold		◆							◆	
Graphite									◆	◆
Indium		◆							◆	◆
Lead		◆			◆	◆			◆	◆
Lithium									◆	◆
Manganese	◆		◆	◆	◆		◆		◆	◆
Molybdenum	◆	◆	◆	◆	◆					◆
Nickel	◆	◆	◆	◆	◆	◆	◆		◆	◆
PGMs							◆			◆
REEs	◆						◆		◆	◆
Silicon		◆							◆	◆
Silver	◆	◆	◆						◆	
Tellurium		◆								
Tin		◆		◆						◆
Titanium				◆		◆				
Vanadium					◆		◆	◆	◆	◆
Zinc	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
Zirconium							◆			

Table 1: Energy transition minerals for moving towards a net zero world
Source: UNEP analysis based on IEA (2022a) and Eurométaux (2022). Analysis by UNEP.

Implications for the mining sector

The energy transition is also a mining and mineral transition. Hundreds of different minerals are needed to make up a wind turbine, an electric vehicle or a solar panel (see Figure 1). However, there are 26 minerals that are particularly important to the energy transition (see Box 1, Table 1 and Annex III). These are a mix of industrial minerals (like graphite), ferro-alloy metals (like vanadium, manganese, nickel and titanium), non-ferrous metals, (like copper, lithium and rare earth elements—a collection of seventeen similar heavy metals) and precious metals and minerals (like platinum-group metals, gold and silver) (IRENA 2023).

The encouraging spread of renewable energy technologies is coupled with the recognition that the pace of deployment needs to speed up dramatically.

The International Energy Agency's Net Zero by 2050 scenario requires a fast deployment of solar, wind and low carbon technologies. It is incredibly ambitious. It is also incredibly mineral hungry (Ritchie 2023). Meeting this trajectory will have a profound impact on the type and quantity of minerals that need to be mined. It will also have environmental and social impacts consequence.

The energy transition is already having dramatic effect on minerals and the mining sector. On the one hand, renewable energy systems do not require the continuous extraction and burning of fossil fuels. A world that is moving towards net zero will need fewer fossil fuels than are currently extracted (in 2022, fossil fuel companies extracted four billion metric tons of oil, eight billion tons of coal and 3.85 trillion cubic metres of gas) (Systemiq 2022). To the extent that renewable energies displace fossil fuels, the energy transition significantly reduces the need for minerals that are dug, sucked or piped out of the ground (Ritchie 2023). On the other hand, humanity will need many more of the minerals used in renewable energy production (wind, water, wave and solar power), use (electric or hydrogen-powered vehicles) and distribution (energy grids). While these technologies do not use mined materials after they are produced, they have high embodied mineral intensity to build in the first place.

The manufacture of a typical electric car uses more than 200 kilograms of energy transition minerals (primarily copper, lithium, nickel, manganese, cobalt, graphite and zinc). This is more than six times the 35 kilograms of copper and nickel that goes into a conventional car. An onshore wind plant needs nine times more minerals and metals per unit of energy produced than a gas-fired power plant. And an offshore wind plant needs roughly 50 per cent more minerals and metals than an onshore one (IEA 2022b).

These figures add up to a significant impact at a global scale. Electric vehicle sales increased by 60 per cent in 2022, exceeding 10 million units (IEA 2023a). Solar photovoltaic installations and wind power installations continue to increase rapidly. Between 2017 and 2022, increased demand from the energy sector was the primary driver of a tripling of overall demand for lithium, a 70 per cent jump in demand for cobalt and a 40 per cent increase in demand for nickel (IEA 2023c). Given that many of the same minerals are used in the smartphones and data centres that power the new digital economy, these minerals are becoming increasingly important to economies in the twenty-first century.

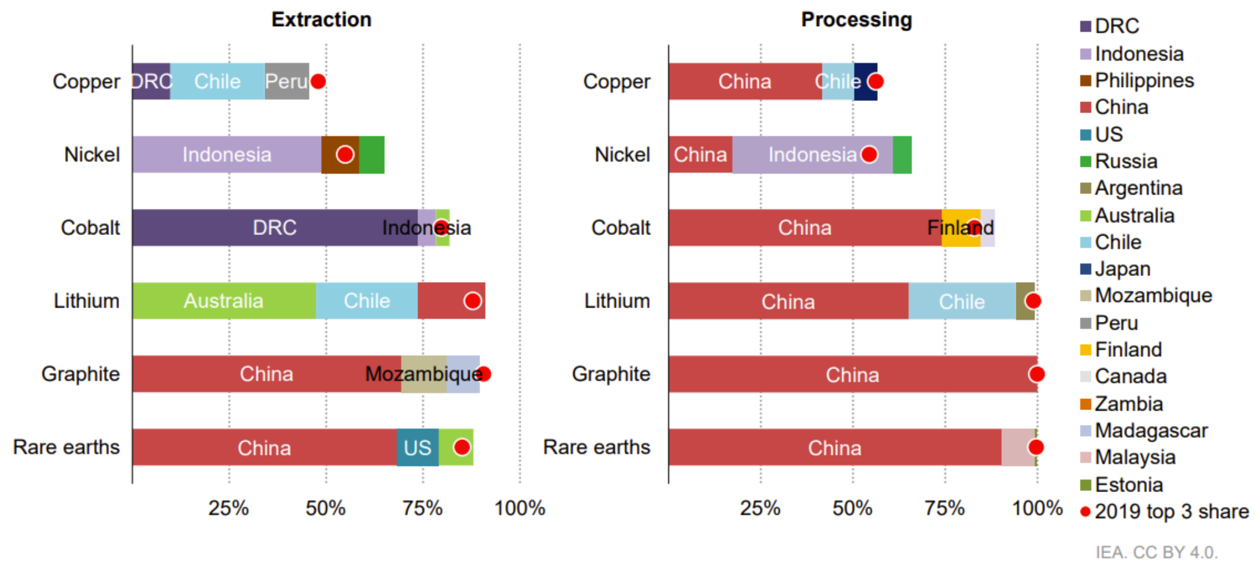
How quickly that demand is projected to rise in the future depends upon many different factors, particularly technological developments, behavioural change and government policies. With that said, the International Energy Agency estimates that climate stabilization efforts consistent with the Paris Agreement (at "well below 2°C global temperature rise") will entail a four-fold increase in mineral requirements for clean energy technologies by 2040. This is a figure that rises to a six-fold increase by 2040 in the more ambitious scenario of striving to reach net zero globally by 2050 (IEA 2022b). This includes particularly dramatic jumps in the demand for specific minerals including an increase of 42x for lithium, 25x for graphite, 21x for cobalt, 19x for nickel and 7x for rare earths in 2040 compared to 2020 (IEA 2022b).

Equipping the energy transition

Existing supply chains have sometimes struggled to meet surging demand for energy transition minerals. In both 2021 and 2022 lithium demand exceeded supply, despite a roughly 180 per cent increase in production since 2017

There has been limited progress in terms of diversification over the past three years; concentration of supply has even intensified in some cases

Share of top three producing countries in total production for selected resources and minerals, 2022



Notes: DRC = Democratic Republic of the Congo. Graphite extraction is for natural flake graphite. Graphite processing is for spherical graphite for battery grade.
Sources: IEA analysis based on S&P Global, USGS (2023), Mineral Commodity Summaries and Wood Mackenzie.

Figure 2. The concentration of mineral supply chains.
Source: Critical Mineral Markets Review, 2023. IEA

(IEA 2023a). While some materials, silicon, titanium and zinc, are in relatively plentiful supply, others, like manganese, nickel and niobium, have limited availability. Some, like gallium, germanium and graphite, are very limited or geographically constrained. On current trends, existing mines and processing facilities will not be able to meet the forecasted demand for all the minerals needed to stay on track for the sorts of energy scenarios where the Paris Agreement is delivered (IEA 2022b).

There are several reasons why the supply of minerals key to the energy transition tends to be both constrained and unpredictable:

◊ **Extraction and processing are dominated by a small number of countries and companies:** Roughly half of the global supply of cobalt comes from the Democratic Republic of the Congo (DRC), 80 per cent of lithium comes from just three countries (Australia, Chile and Argentina), 60 per cent of the global supply of manganese comes from South Africa, China and Australia and 88 per cent of the global supply of rare-earth elements comes from China alone (Nakano 2021). Indonesia and the Philippines jointly produce 45 per cent of global nickel output, a figure that is set to increase to 70 per cent by 2025 (IEA 2022b). The pattern is even more pronounced at the processing stage (see Figure 2). China has emerged as a particularly important player in global mineral processing. It handles 40 per cent of copper, 35 per cent of nickel, 58 per cent of lithium, 65 per cent of cobalt and 87 per cent of rare earth elements (IRENA 2023). This concentration of extraction and processing makes the supply chain inherently less competitive and vulnerable to logistical risks and natural disasters. It also makes it sensitive to geopolitically induced disruptions, such as trade restrictions and hoarding behaviours (Leruth et al. 2022). For example, disruptions to the supply of platinum from South Africa could affect around 70 per cent of the global supply of processed platinum, with potentially serious consequences for the production of hydrogen fuel cells, which require the valuable metal (Ali et al. 2022).

◊ **New mines typically take a long time to develop:** The average mining project takes 16 years to get from discovery of the minerals to first production (IEA 2022b). This means there is often a significant lag in how fast supply can react to demand. This is problematic in the context of the sustainable energy transition's anticipated sharp increase in demand for the supply of key minerals as it is uncertain that suppliers will be able to quickly ramp up production to meet corresponding increases in demand.

◊ **Climate and water risks:** Several important reserves of energy transition minerals are highly exposed to climate risks and/or in areas that are highly water stressed. Copper and lithium production relies on large amounts of water for processing. However, more than half of today's lithium and copper production is located in areas that suffer high levels of water stress (IEA 2022b). An estimated 32 per cent of copper mines and 39 per cent of iron ore mines are in areas of moderate to high water scarcity (AlphaBeta 2017). Major producing regions including Australia, China and Africa are subject to extreme heat, drought and flooding.

◊ **Declining ore grades mean that more mining may be needed for the same amount of end product:** Compounding the supply challenge is a general trend towards declining grades of ore for some minerals, particularly copper. Many of the world's easily accessed and exploited mineral deposits have been mined. Average grades of copper (i.e. the amount of the metal within the ore body), have been falling. This means that the deposits that are now being mined are often of a lower grade and further away from energy and transportation infrastructure. Current operations are extracting ore with an average of 0.53 per cent copper, while those under development are averaging only 0.39 per cent (McCrae 2018). This is important because extracting the same amount of metal from lower-grade ores produces more waste rock and needs more energy. This increases both production costs and greenhouse gas emissions.

Consequences of tight, unpredictable supply chains

Although supply is expanding, on current trends there are likely to be significant shortfalls in six key minerals by 2030: graphite (45 per cent shortfall of demand), cobalt (40 per cent), lithium (30 per cent), neodymium (30 per cent), nickel (15 per cent) and copper (10 per cent) (ETC 2023a). It remains to be seen whether these are short-term supply chain issues that will be resolved in the coming years, or whether they are structural long-term bottlenecks that will impact the direction and extent of the energy transition (Gielen 2021). The consequences of these tight and fragile supply chains are already playing out in a number of ways:

◊ **Volatile prices:** The discrepancy between the supply and demand of many energy transition minerals is resulting in volatile prices. The price of lithium carbonate increased between December 2020 and December 2022 (Bazilian and Moores 2023), before falling back to 2020 levels by mid-2024 (World Bank 2024). This kind of boom-bust volatility inhibits investment and makes the energy transition more costly (Simas, Aponte and Wiebke 2022). This volatility is exacerbated by the nature of the trade in many energy transition minerals. Unlike fossil fuels, which are traded in standard amounts on financial exchanges with clearly listed prices, minerals are primarily sold through negotiated bilateral contracts between producers and consumers (IRENA 2023). This means there are no universally accepted benchmark prices for most minor metals.

◊ **Barriers to building new low-carbon energy systems:** As learning and economies of scale bring down the cost of other components, the mineral inputs are taking up an increasingly high share of the total cost of batteries and other clean energy technologies (IEA 2022b). In 2021, the head of the IEA warned that high copper prices (which had risen above US$10,000 per ton) could add half a trillion dollars to the cost of reaching climate goals over the two decades to 2040 (Sanderson and Sheppard 2021). The volatility in prices also affects the profitability of key producers, which can further reduce competition in the market and raise prices over the long-term (ETC 2023b). Higher input costs for the necessary minerals will slow what has been a steady decline in the price of batteries, leading to a later 'cost parity' date between electric vehicles and internal combustion engines, pushing up end prices for electric vehicles (EVs) and slowing their uptake across the world (IEA 2023b). An analysis of the adoption of electric vehicles in China estimated that higher material costs would mean that the number of EVs in circulation by 2023 would be 35 per cent compared to nearly half (49 per cent) under the baseline situation (Wang et al. 2023).

◊ **Growing economic protectionism:** Countries are taking a nation-first approach to securing access to energy transition minerals, through cooperation where possible, but also through a securitised approach that seeks to control access to resources (Kalantzakos 2023). The growing importance of energy transition minerals has led to a proliferation of measures to influence and control markets. These fall into two broad camps. There are 'buyers clubs' where import-dependent countries are trying to band together to have more influence in the market. There are also export controls imposed by producing countries seeking to ensure domestic supply before exports and/ or higher returns for their products. Globally, there are five times more trade restrictions on energy transition minerals exports than there were in 2009 (IEA 2023c). In fact, the Organisation for Economic Co-operation and Development (OECD) estimates that 10 per cent of the value of energy transition minerals is now subject to at least one trade restriction (OECD 2023). Some of the public policy measures that rich countries are putting in place may be putting developing countries at a competitive disadvantage as they cannot afford similar subsidy programmes. This ultimately limits their ability to roll out the green transition.

◊ **Rising geopolitical tensions:** The importance of energy transition minerals to future economic development (for example, in the semiconductor industry and digital infrastructure) and the military (in modern intelligence and defence systems) means they are becoming geopolitically contested (Livingstone 2021; Riofrancos 2022). Many countries and regions are highly dependent on imports for their supply of energy transition minerals. The European Union, for example, is between 75 per cent and 100 per cent reliant on imports for most energy transition minerals (European Commission [EC] 2020). A number of initiatives have been set up to deal with the security of energy transition mineral supply at a national scale (i.e. developing national reserves, developing stockpiles and long-term supply contracts). However, truly international approaches are lacking (Gielen 2021). Despite the common perception that China dominates energy transition mineral supply chains, the country is actually among the most dependent on imports. Indeed, it is the world's biggest importer of nickel, copper, cobalt and rare earths (IRENA 2023).

- **New company strategies:** The geopolitical landscape is also shifting the landscape for mining companies in terms of their investment choices, competition, production schedules (IEA 2022a; IEA 2022b). For example, the world's largest mining company by market capitalization, BHP, is hiving off its oil, gas and coal businesses and positioning itself as a mining company that is focused on the energy transition. Meanwhile, the security of the lithium supply has become such an issue for technology companies in the United States of America and in Asia that some companies have begun to form strategic alliances with lithium exploration companies worldwide, a form of vertical integration designed to assure supplies of necessary minerals from mine to product (Kalantzakos 2019).

Summary

- The world gets nearly 80 per cent of its primary energy supply from fossil fuels. This needs to change quickly to avert dangerous climate change. The challenge is to simultaneously decarbonise the global energy system while expanding energy access to hundreds of millions of people.

- Costs of renewable energy technologies continue to drop compared to fossil fuel alternatives. The speed of their deployment is accelerating. However, the pace of deployment needs to triple to stand a realistic chance of meeting the Paris Agreement goal of warming that is substantially less than 2ºC.

- A group of 26 minerals, which have a range of specialised uses in renewable energies and electric mobilities, are critical for the energy transition. These minerals are produced and processed in a wide variety of ways across the globe at all scales from artisanal miners with a shovel to multibillion dollar large-scale mining and processing operations.

- There is soaring demand for these minerals and most analysts expect that significant additional supplies of energy transition minerals will be needed to equip the energy transition.

- However, the supply of these minerals is far from certain amid a trend of declining ore grades, long lead times for new mining operations and a limited number of countries and companies extracting and processing the minerals. Supply challenges could slow down the energy transition or make it more expensive and unequal.

- The prices of energy transition minerals are becoming high and volatile. Rising geopolitical tensions, interference in markets and strong political pressure to expand mining (often into environmentally and socially sensitive areas) are adding to these problems.

- There is a high risk that, without change, the benefits of the transition could be lost to lower income countries, further eroding trust. Equity remains core to a successful transition based on access, affordability and benefit sharing.

II. Mining for the green energy transition carries environmental risks

Mining is, by definition, an extractive industry that can pose threats to the environment and surrounding communities. Despite covering a relatively small portion of the globe (around one per cent), surface mining is identified as a driver of biodiversity loss worldwide. It often has a more significant negative effect on local biodiversity than agriculture (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES] 2019). If the increased demand for just five of the energy transition minerals identified in this report (copper, nickel, lithium, cobalt and graphite) were sourced from new mines, the world would need 145–245 additional mines by 2030 (ETC 2023a).

This section explores some of the social and environmental costs of current mining practices. It highlights how these could expand if the energy transition is primarily equipped from new mining. It attempts to uncover the trade-offs that could occur as a result of the energy transition. How policy makers approach these trade-offs will determine the trajectory of the green transition.

Impacts on climate, nature and pollution

If not carefully managed, the mining of energy transition minerals and the production, use and disposal of renewable energy technologies will contribute to climate instability, biodiversity loss and rising levels of pollution (see Figure 3).

Activities like mining can impact local communities and the environment through three pathways. They can be through direct pathways whereby ecosystems are explicitly removed to extract minerals or communities directly impacted. They can be through indirect pathways, whereby an influx of people coming to pursue economic activity associated with a mine site causes ecological damage. They can be cumulative pathways, whereby additional impacts of other mine sites in the immediate landscape compound a single site's impacts. Impacts through the full life cycle should be assessed, from extraction of raw materials to the disposal of products at the end of their life. This is especially important for the energy transition and minerals that may have significant social and environmental costs in their disposal as much as in their extraction and production. For example, electrolytic manganese residue, commonly produced in battery manufacture, presents a great risk to human and ecosystem health and is routinely disposed of in waste landfill sites with no pre-treatment (He et al. 2021; Wang et al. 2022). Ultimately, mining minerals for the clean energy transition inefficiently and in larger volumes than those that are strictly necessary risks a continuation of the social and environmental harm that has defined much of the past century of human impact.

One particularly visible impact is the waste material, also known as tailings, created as by-product of mining. Copper ores tend to contain roughly 0.6 per cent elemental copper, whereas bauxite contains around 25 per cent elemental aluminium, resulting in very different amounts of ore and metal that need to be moved and processed for every ton of metal obtained (ETC 2023a). And as ore grades decrease, the amount of energy and water needed and the emissions produced to obtain one ton of metal, will correspondingly increase (ETC 2023a). The social and environmental impact of tailings and their required long-term monitoring is rarely considered at the planning stage (UNEP 2024a). A recent assessment found that 9 per cent of 1,721 disclosed tailings storage facilities globally are within protected areas, with 20 per cent of them within 5km of such areas (Aska et al. 2024).

The production of minerals and metals is both energy and water intensive. Mining activities can accelerate the risk of water scarcity as well as its effects. Over 50 per cent of lithium production today is in regions with high water stress levels and 80 per cent of Chile's copper production is from highly water stressed arid regions (IEA 2022d). This can be a source of conflict in arid areas with competing water demands for people, industry and agriculture (International Resource Panel [IRP] 2023).

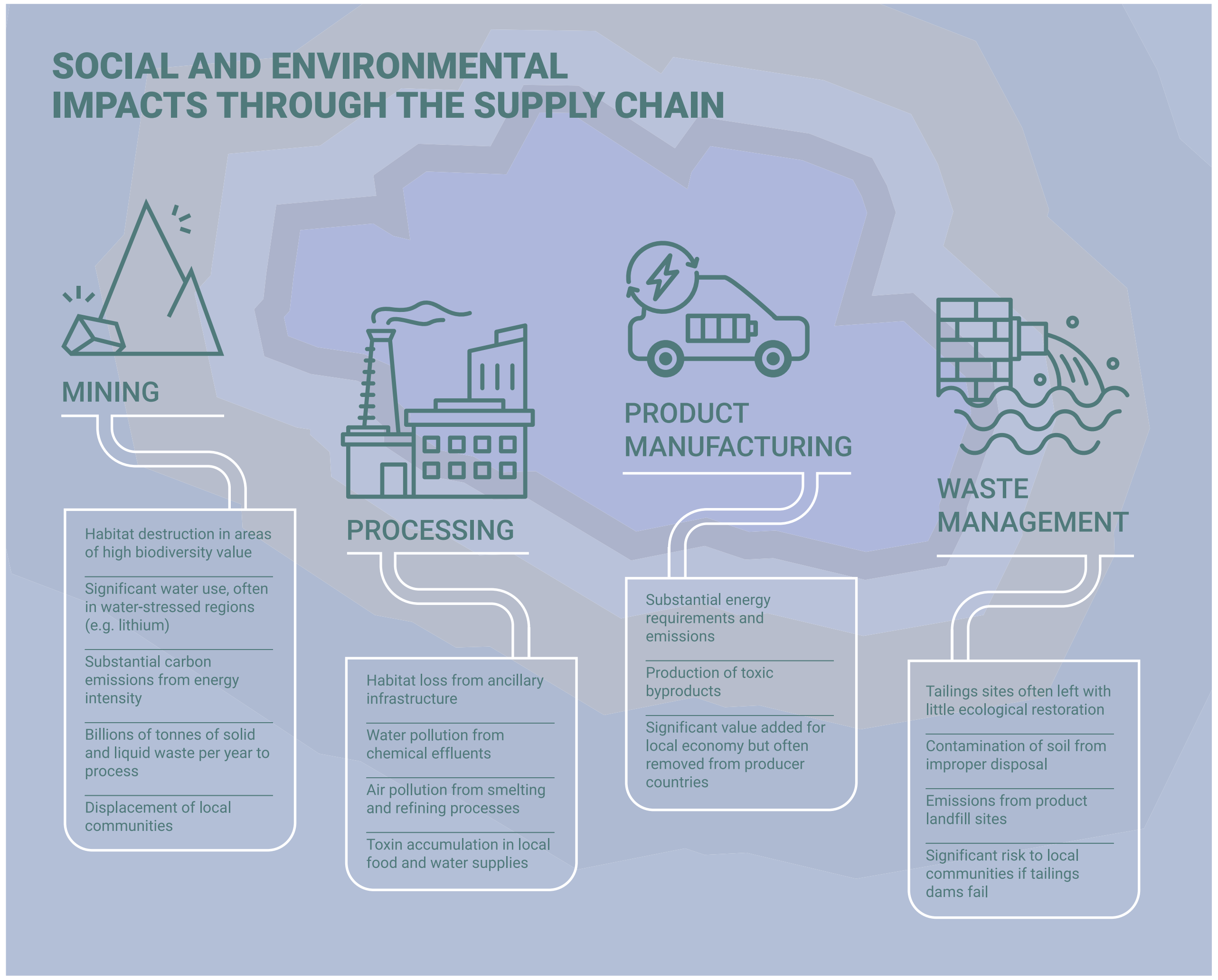


Figure 3: Minerals have different social and environmental impacts through the supply chain.

While there are significant barriers to the participation of women in mining activities meaning that women derive less benefits from mining operations. they are also disproportionately affected by the negative impacts of mining activities. Research shows that the establishment of new mining projects often leads to increased gender-based violence in surrounding communities, while also showing that women suffer greater impacts from the health problems, involuntary resettlement, environmental damage and social disruption associated with mining activities (International Institute for Sustainable Development [IISD] 2023).

Uncharted waters: Deep sea mining

Supply challenges of minerals key to sustainability transitions are encouraging miners to move into new areas that may be even more environmentally sensitive. One particularly sensitive frontier, the deep seabed, has large supplies of energy transition minerals in the form of polymetallic nodules, polymetallic sulphides and cobalt rich ferromanganese crusts. These are often found in international waters. Their extraction could cause serious environmental challenges in fragile marine ecosystems (Crane et al. 2024).

Polymetallic nodules, which are essential for some specialised marine life, grow extremely slowly. This makes them non-renewable resources over the course of a human lifetime. The ocean is an extremely slow, low energy environment. Indeed, one experiment showed that the seafloor has still not recovered 26 years after simulated mining activity (Simon-Lledó et al. 2019). Deep sea mining can cause further problems in the water column through noise, light and sediment pollution. It can also cause temperature fluctuations that are harmful to marine life. This has raised concern that midwater ecosystems, comprising roughly 90 per cent of the biosphere, are not being adequately accounted for when mining activities are being scrutinised (Drazen et al. 2020).

Given the large uncertainties associated with deep sea mining and the scientific unknowns, UNEP and many other scientific organizations are suggesting the use of the precautionary principle. This principle advocates for detailed assessment of all available scientific evidence, and to consider that, while the potential economic benefits of deep sea mining are becoming clearer, the full economic costs are not yet apparent and are potentially very negative (UNEP 2024b).

Uneven distribution of negative and positive social impacts of mining

Given the urgent need for decarbonization and multilateral agreement on courses of action, what are the alternatives?

The mining of minerals is a powerful economic force that can bring benefits but also harms. Mining can create jobs, boost local economies and improve economic prospects. A 2022 estimate suggested that the mining sector contributes upwards of 24.2 million jobs globally (Arendt et al. 2022). In the same year, the mining industry's leading 40 companies had a total revenue of approximately US$943 billion. The mining of minerals and metals remains an important contributor to the economies of many lower or lower-middle income countries (International Council on Mining and Metals [ICMM] 2022). By enhancing infrastructure and facilitating access to necessary services, like healthcare and education, responsible mining practices can be harnessed as an opportunity for sustainable regional and local development.

But mining can also provoke social tensions brought on by wealth disparity and exacerbated by corruption and unequal distribution of extraction advantages.

Land use and territorial rights disputes can result in the confiscation of local property and the forced displacement of residents, disproportionately affecting women who rely on small-scale agriculture and other subsistence activities. Influx of foreign labour can also increase pressure on infrastructure, undermine cultural identity, reduce the supply of housing and raise living expenses for locals. Mining can create legacy liabilities in the form of tailings, contaminated run-off and other mining waste (IEA 2022b).

Safety and labour conditions in and around mining operations are paramount. The health of local communities can suffer greatly as a result of the environmental effects of mining. This can arise from direct exposure to toxic substances in the water and air or from indirect effects like contamination of important nearby resources or a reduction in the availability of those resources (Spohr 2016). Because mining involves exposure to airborne dust, chemicals and other particles, it has been linked to an increase in skin and respiratory conditions. Exposure to harmful chemicals and pollutants can have severe health impacts on women, including reproductive health issues. In addition, poor living circumstances and limited medical precautions among workers fuel the development of infectious diseases. This underscores the connection between environmental and public health concerns. Regarding employment and labour working conditions, women often face significant barriers to entry in the mining sector, including discrimination, lack of access to training and cultural biases. Working conditions in mines can be particularly harsh and unsafe for women, with inadequate facilities and higher risks of gender-based violence (International Labour Organization [ILO] 2021).

Some energy transition operations have also been implicated in human rights abuses such as child labour. Indeed, surveys show that about 30 per cent of the sites in one African country employ children. Additionally, the fact that 54 per cent of essential minerals are located on or close to the territory of indigenous peoples highlights how vulnerable these communities are to exploitation. When mining earnings are not reinvested in the host community or if traditional sources of income are disrupted, there is a risk of increased poverty.

These forces can be particularly pronounced in the context of existing fragility or conflict that themselves drive poverty. For example, the production of platinum (Zimbabwe), rare earth elements (Myanmar), graphite (Mozambique) and cobalt (DRC) are each one of the top three producers globally of the associated critical energy transition minerals and are also considered by the World Bank to be fragile or conflict affected regions.

Conflicts resulting from mining operations are frequently caused by differences in the distribution of burdens and financial gains. Tensions between local populations and mining firms, as well as internal conflicts, can result from disputes over land use and economic rewards. Additionally, widespread national corruption has a significant negative social impact since the mining industry's high financial stakes can encourage unethical behaviour at different levels of government. This impedes equitable benefit distribution.

Difficulties in resolving these environmental tensions are exacerbated when energy transition mineral reserves overlap with other priority areas for sustainability, such as indigenous areas or lands belonging to local communities. Recent analysis suggests that as much as 68 per cent, or 2,409 individual energy transition mineral mining projects, are located on or near indigenous or lands belonging to local communities (Owen et al. 2022).

Transparency of sustainability performance is currently lacking for the mining sector. While many companies fall under more general reporting regulations due to their size, there are few mining-specific sustainability reporting requirements (UNEP 2020b). Recent guidance from the IEA stressed the necessity of improving industry-wide data collecting and reporting standards. This should be made possible by directives from governments to support benchmarking and improve monitoring throughout the supply chain (UNEP 2020b). Encouraging businesses to increase supply chain transparency (including through conducting due diligence and publicly disclosing risks and mitigation measures) is a critical first step in reducing social and environmental risks. It is also essential for arming stakeholders with the data they need to make decisions that are sustainable.

Focus on the net benefit

Some commentators have used scare tactics around the environmental implications of a large increase in mineral mining as an argument against the green energy transition and for the continued use of fossil fuels (IRENA 2023). However, it is important to remember the implications of an alternative world that does not grasp the opportunity of the green transition.

The Energy Transitions Commission (2023a) notes that achieving net zero with clean energy systems will have roughly twice the land and water demands of the fossil–fuel-based energy system. They estimate that net zero clean energy systems will require three quarters of a million square kilometres of land globally and annually use 58 billion cubic metres of water (see Figure 4).

To put this in perspective though, it is critical to note that this is less than 2 and 1 per cent of the amount of water and land consumed by global agricultural systems. And the emissions needed to produce all the minerals for a clean energy system will be a total of around 40 gigatons of CO2 equivalent, which could fall towards zero if mining systems decarbonise. Meanwhile, the increase in energy transition mineral mining could result in up to 13 billion tons of waste rock each year, but this is less than the 15 billion tons of fossil fuels that are currently extracted and burned each year (ETC 2023a). And that is before considering the health and development benefits of the energy transition. Indeed, some researchers estimate that the reduction in air pollution related deaths and the carbon mitigation from the substitution of fossil fuels by renewable energies has already saved around 80 million lives between 2000 and 2020 (Sovacool and Monyei 2021).

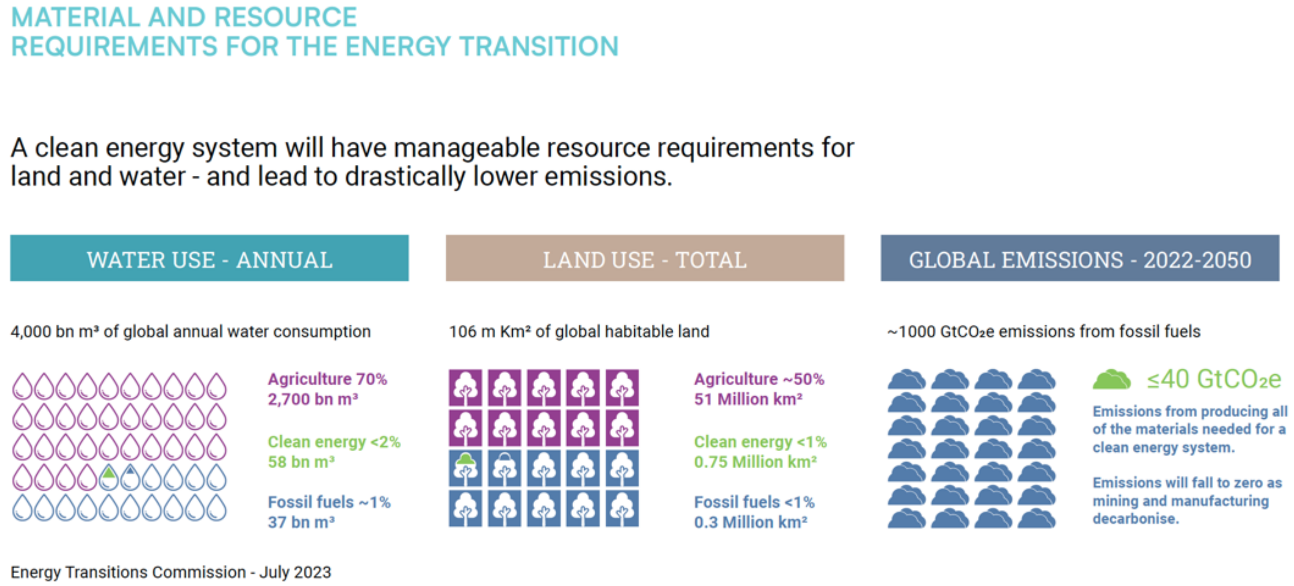


Figure 4: Water, land, and greenhouse gas emission use of a clean energy system.
Source: ETC 2023

[6] The complexity of the demand and supply curves and technology projections for each of the 26 very different minerals featured in this report mean that it is extremely challenging to develop projections for the possible contribution of efficiency and circularity to future demands for these minerals. The 48 per cent figure is used here as merely indicative and should not be understood as a modelled projection.

Summary

◊ Surface mining, despite covering one per cent of the global surface area, can pose significant threats to biodiversity through increased toxicity, pollution and rising greenhouse gas emissions with severe consequences for local communities.

◊ Terrestrial mining activities can lead to water scarcity and contamination. This affects over 50 per cent of lithium production in high water-stress regions.

◊ Mining can contribute to conflict, corruption, demographic changes, gender inequalities and violations of human rights. Indigenous populations and women are particularly vulnerable to these threats.

◊ Balancing the demand for critical minerals with environmental and social considerations poses challenges, necessitating improved governance, supply chain transparency and sustainable mining practices.

III. Equity, efficiency, circularity and responsibility

Introduction

The prospects of a truly 'sustainable' energy transition face two opposing challenges. The first is the risk of short-term supply shortages of key energy transition minerals as a result of supply chain constrictions and the time it takes to open new mines, which could delay the roll out of the energy transition. The second is the serious environmental and social consequences if mining expands without careful management.

Greater efficiency, circularity, and responsibility in the use of energy transition minerals throughout their life cycle can help to address both challenges. Research by the Norway based research organisation, SINTEF, modelled the mineral requirements for the IEA's net zero scenario. They assessed future demand curves for seven energy transition minerals (or groups of minerals)—lithium, manganese, cobalt, nickel, rare earth elements, platinum and copper—under four different scenarios. First was a current technology scenario, which describes the mineral demand if we used the same technology as in 2021.

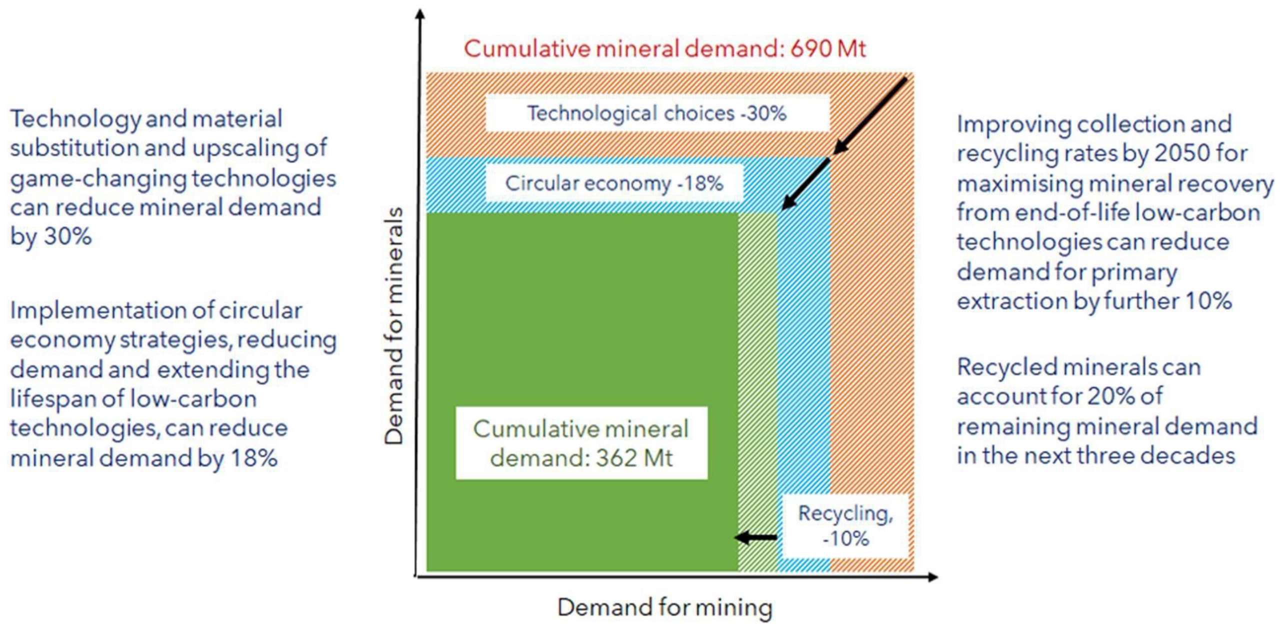


Figure 5: The impact of efficiency and circularity on cumulative demand for energy transition minerals.
Source: Simas, Aponte and Wiebe, 2022

Second was a business-as-usual scenario, which describes the evolution of different technologies based on existing patterns, learning curves and industry signals. The third scenario was modelled on a future where chemistries low in critical energy transition minerals made up the majority of the installed capacity. The fourth was an advanced technology scenario, where new technologies low in critical energy transition minerals take off and become a larger share of the market share of annual installed capacity by 2050 (Simas, Aponte and Wiebe 2022).

The researchers calculated that under a business as usual scenario the cumulative mineral demand between 2022 and 2050 for these seven minerals would be 690 million tons. They projected that technological developments to increase the efficiency of the use of energy transition minerals and rolling out game changing technologies could reduce that projected demand by 30 per cent. Moreover, the implementation of more circular strategies could reduce cumulative mineral demand by a further 18 per cent. Improving the rates of recycling, which they estimate could account for a 10 per cent drop in projected demand, does not affect the overall demand for minerals, but it does reduce the overall demand for new mines. Cumulatively then, SINTEF estimates that more efficient and circular approaches to the deployment of the energy transition could bring down the cumulative need for the seven minerals featured in the report by nearly half between now and 2050 (see Figure 5) (Simas, Aponte and Wiebe 2022).

In future work we will model the implications of the implementation of circular strategies, improving the rates of recycling and technological developments on the 26 critical minerals identified in this working paper. This has potentially sizable benefits in terms of side-stepping the trade-offs that would be interwoven in a mineral-heavy energy transition. It would reduce costs, reduce environmental damage, avoid supply gaps, mitigate geostrategic tensions and facilitate the uptake of the green transition.

Doing more with less, better, and for longer

Accelerating the energy transition while minimizing its material footprint must be a priority over the coming decades. Ultimately, our 'business-as-usual', linear model of production to consumption to disposal will not meet the increasing demand for the minerals required to support the sustainable energy transition within planetary boundaries (UNEP 2020a).

But it is important to be clear-eyed about such a daunting task. The fossil fuel sector took more than a century to reach its current state of maturity. By contrast, achieving net zero means the clean energy sector must scale up and roll out almost universally in around 25 years. That will be hard. It will require creating a supportive environment for innovation and investment, ensuring that necessary steps are not overlooked and helping to accelerate the transition from innovation to commercialization. This means we must simultaneously deliver three paradigm shifts of greater efficiency throughout all renewable energy technologies, a more circular economy and more responsible approaches towards mining that will still be needed as the energy transition ramps up.

A new, circular, efficient energy system involves extracting far smaller quantities of key energy transition minerals for use in structures and technologies that generate, store, transmit and harness clean energy. Many, though not all, energy transition minerals can be recycled over and over again (Turner 2023). This is inherently more sustainable than the current fossil-based system where billions of tons of coal (8 billion), oil (4 billion) and gas (3.85 trillion cubic metres) are extracted to be burned just once. Remarkably, a conservative estimate of the expected total mineral requirements for the energy transition between now and 2050 will still be less than one year of coal burning (ETC 2023a).

Efficiency

Efficiency relates to the ability to achieve more 'work' from a given input (of material, effort or time). In this context, it refers to ways to ensure that a given amount of energy transition minerals delivers more of a particular service, whether this is energy generation, energy transmission or energy storage. A related concept is 'sufficiency', which relates to having enough of a particular service to achieve the social goal. For example, a smaller, lighter car gets people from "A" to "B" just as well as a larger, heavier suburban utility vehicle.

Renewable energy technologies are in a period of dynamic technological change. This is increasing material efficiency and reducing the quantity of energy transition minerals needed for a given task. Innovation in green energy technologies can shape the demand for energy transition minerals by enhancing efficiency, optimizing designs, increasing longevity and incorporating new materials. Meanwhile, increasing energy efficiency in buildings, transport, appliances and industrial processes will also impact the future demand for energy transition minerals.

However, many game-changing innovations are still years or decades away from large-scale commercialization (Burke et al. 2022). The market is likely to experience further shifts before eventually consolidating around a limited number of materials and technologies (IRENA 2023). New technologies and material substitution, if scaled up, can reduce future demand for energy transition minerals by 30 per cent (Simas, Aponte and Wiebe 2022). They can also shift the balance of power between consumer and producer countries, particularly as innovation can completely alter the commercial value of certain minerals.

Circularity

Circularity is where products are designed in such a way that they can be reused, remanufactured, recycled or recovered. This allows them, and the materials from which they are made, to be maintained in the economy for as long as possible. The appeal of circularity in mining lies in its broad value proposition, which promises benefits for the economy and business competitiveness. It also helps to present new solutions for environmental concerns (Lacy and Rutqvist 2015).

Unlike fossil fuels, which are inherently single use (burned and lost), energy transition minerals are, for the most part infinitely recyclable. As such, these minerals are especially suited to circular economies (ICMM 2022). A range of policy mechanisms can help to ensure that minerals are retaining the economy for longer, that products are reused in second and third 'lives', that more mineral is recovered and that products are more effectively recycled when they reach the end of their lives. Done well, circularity in minerals can also deliver benefits to producer countries – but this will require social innovation, new business models and increased traceability. Circularity could then facilitate reaching the second actionable recommendation from the UN Secretary General Panel on Critical Energy Transition Minerals, which calls for "a global traceability, transparency and accountability framework along the entire mineral value chain – from mining to recycling".

Responsibility

Responsible mining is where the social and environmental costs of mining are minimised and the benefits to local communities and national economies are maximised. Mining will always be extractive and, by definition, not indefinitely sustainable. However, there are numerous examples of best practices in the planning, implementation, monitoring, community engagement and closure of mine sites that can help to improve the overall footprint of mining (UNEP 2023b).

We are at the beginning of what could be an extended opportunity period for countries with reserves of energy transition minerals. In a sign of the changing times, revenues from energy transition minerals are due to outpace revenue from coal by 2040 (ETC 2023a). With proper revenue and benefit sharing

agreements put into place, these reserves could increase national revenues and help communities retain value-added benefits from the supply chain. They can also boost employment in the mining sector. In 2022, an estimated 800,000 people were working worldwide in the mining of copper, cobalt, nickel and lithium. This was a jump of 25 per cent on the previous year (IEA 2023d).

The growing demand for energy transition minerals in producing countries is an economic opportunity, but also an environmental risk. The proper stewardship of revenue from mining industries has the potential to lift a lot of people out of poverty. Moreover, well-managed minerals and metals can be a source of revenue for developing countries. The UN Secretary General's Panel on Critical Energy Transition Minerals emphasises the need for investments, finance and trade to be responsible and fair, in its fifth principle. Indeed, when collected and distributed with transparency, revenues from minerals can support national

investments in health, education, infrastructure and other sectors crucial to a country's growth and prosperity. However, countries engaged in the extraction of energy transition minerals are rarely the source of manufacturing or mineral processing. This means they are often missing out on opportunities to gain benefits from the mineral economy (Bazilian and Moores 2023).

Meanwhile, other countries have turned to export bans and other measures to encourage more investment in processing the minerals within their borders, though these have occasionally proved counter-productive by suppressing the price of domestic minerals and disincentivizing foreign direct investment (Davis 2020). More than 50 countries have set restrictions or duties on raw materials (UNEP 2023b). Other resource-rich developing countries, such as Indonesia, Zambia and Zimbabwe, have implemented export bans on raw materials, and have attracted investment for the processing of raw materials (especially nickel, in the case of Indonesia). This processing is fast becoming an increasingly important source of economic growth (Climate Rights International [CRI] 2024).

But without thoughtful attention paid to linkages and mechanisms to promote wider growth, mining can have very little positive economic impact on communities. This means countries can be left bearing serious environmental and social impacts while gaining little from the mining that has taken place. Much of the early stages of large mine development is done by junior mine companies that are typically looking to 'flip' their assets to a larger miner. As such, these junior companies have a vested interest in keeping a low profile. This misses an opportunity to proactively engage with stakeholders and get inputs on how the mine could be meeting better environmental standards.

GUIDING PRINCIPLES ON CRITICAL ENERGY TRANSITION MINERALS

The United Nations Secretary General's Panel on Critical Energy Transition Minerals proposes seven voluntary Guiding Principles, building on existing norms, commitments and legal obligations outlined in United Nations texts:

PRINCIPLE 1
Human rights must be at the core of all mineral value chains.

PRINCIPLE 2
The integrity of the planet, its environment and biodiversity must be safeguarded.

PRINCIPLE 3
Justice and equity must underpin mineral value chains.

PRINCIPLE 4
Development must be fostered through benefit sharing, value addition and economic diversification.

PRINCIPLE 5
Investments, finance and trade must be responsible and fair.

PRINCIPLE 6
Transparency, accountability and anti-corruption measures are necessary to ensure good governance.

PRINCIPLE 7
Multilateral and international cooperation must underpin global action and promote peace and security.

ACTIONABLE RECOMMENDATIONS

To embed and maintain these Guiding Principles across critical energy transition mineral value chains, the Panel has made a number of actionable recommendations that leverage the United Nations in the creation of key bodies and processes. These include the establishment of:

A High-Level Expert Advisory Group to accelerate greater benefit-sharing, value addition and economic diversification in critical energy transition minerals value chains as well as responsible and fair trade, investment, finance, and taxation.

A global traceability, transparency and accountability framework along the entire mineral value chain – from mining to recycling – to strengthen due diligence, facilitate corporate accountability and build a global market for critical energy transition minerals, though the framework should not be used as a unilateral trade barrier.

A Global Mining Legacy Fund to build trust and address legacy issues as a result of derelict, ownerless or abandoned mines, and strengthen financial assurance mechanisms for mine closure and rehabilitation.

An initiative that empowers artisanal and small-scale miners to become agents of transformation to foster development, environmental stewardship and human rights.

Equitable targets and timelines for the implementation of material efficiency and circularity approaches across the entire life cycle of critical energy transition minerals.

Source: (UN Secretary-General's Panel on Critical Energy Transition Minerals 2024)

The critical importance of equity

To be sustained and sustainable, the energy transition must be fair, equitable and gender-just, particularly for the poorest people in the least developed countries (Ngum and Kim 2023). This means that, alongside ramping up efforts to decarbonise energy production and use, the world also needs to massively extend modern energy access to the 754 million people currently living without electricity as well as to the 2.4 billion people who are cooking on unsafe fuels (IEA 2022a). In other words, the energy transition is not just a 'retrofitting' exercise to swap out fossil fuels for renewable infrastructure, it also must be a massive 'extension' exercise to provide energy services to those who do not currently enjoy them.

This is important as efforts to move towards the green transition and greater circularity need to recognise the differentiated responsibilities implicit in countries' historical emissions. The pace and nature of circularity needs to be different. In practical terms this means that rich countries should aim for an absolute decoupling of virgin resource use from economic growth, whereas developing countries need to aim for a relative decoupling from resource use, recognizing that they need to continue growing demand in order to develop basic infrastructure (Pedro 2023; Potocnik and Teixeira 2023).

This also means that mineral-rich but developing and least developed countries should be afforded the opportunity to use their mineral wealth to develop their economies, infrastructure and communities. Africa, for example, already produces 80 per cent of the total world supply of platinum, 50 per cent of the manganese, 66 per cent of the cobalt and significant amounts of chromium. It is thought to have some of the largest untapped reserves of energy transition minerals; but because of a lack of systematic exploration, the full extent of the region's mineral base remains unknown (Singé 2021).

For these countries and communities, the energy transition represents enormous potential for prosperity through jobs, revenue and human capital. The realization of this potential hinges on how energy transition minerals are extracted and how host countries and communities benefit from their extraction, including through the judicious use of rent and royalty schemes to provide for national and regional income and capital investment. It also hinges on whether there are effective safeguards, policies and monitoring systems established to ensure minimal environmental impacts, maximum benefit sharing and significant engagement between local communities and the mining industry. Finally, it means ensuring that developing countries are fully included in circular economy supply chains through investment in advanced manufacturing processing, production and recycling facilities (Bazilian and Moores 2023). In other words, ensuring equity throughout the energy transition requires extending access to modern energy for communities and providing access to the energy transition minerals that countries need to build their own renewable energy systems.

Progress in technologies and recycling

Innovation in green energy technologies is shaping the demand for energy transition minerals by enhancing efficiency, optimizing designs, increasing longevity and incorporating new materials. An overview of progress includes:

- Over the past thirty years, the energy conversion rates of solar photovoltaic cells have tripled. More recently, the emergence of low-cobalt battery designs has cut the predicted demand for cobalt by half (Turner 2023; ETC 2023a).

[5] A framework for a gender-just energy transition would help ensure the rights of disadvantaged groups are met by addressing the root causes of gender inequality within and along the transition to a resilient and sustainable global energy sector (Ngum and Kim, 2023).

◊ Analysts anticipate that, with the right policies and support in place, battery pack energy could rise from 160 kWh/kg to around 250 kWh/kg by 2030. This would provide the same vehicle range with 35 per cent less material requirements (ETC 2023a).

◊ Other technologies are helping to recover energy transition minerals through agromining (also known as phytomining - using hyperaccumulator plants to gather trace minerals and then harvesting and processing the biomass to recover target metals such as nickel) or biomining (using bacteria and other microorganisms to extract certain minerals from their ores). Copper, gold, nickel, silver, uranium, zinc and cobalt are all minerals that can be extracted through biomining (Columbia Centre on Sustainable Investment [CCSI] 2020).

◊ Many companies are experimenting with new minerals, technologies and processes as a response to the rocketing prices for some energy transition minerals. In July 2023, Toyota claimed it had developed a new, more durable solid-state battery with a range of 1,200 km that could charge in 10 minutes or less, at half the weight, size and cost of current batteries (Davies 2023).

◊ Meanwhile, the world's first factory dedicated to fully recycling solar panels official opened in June 2023 in France. The company estimates that it can extract and recycle up to 99 per cent of solar photovoltaic components (Gordon 2023).

Meanwhile, action at national and international levels is helping to create an environment for greater efficiency and circularity. It is also helping to improve the performance of mining:

◊ In the EU more than 50 per cent of metals, such as iron, platinum and zinc are recycled. This provides more than 25 per cent of the EU's consumption, though with some minerals particularly relevant for renewable energies, such as rare earths, gallium or indium, secondary production makes only a very small contribution to meeting demand (EC 2020). In the United States of America, recycling is currently equivalent to 29 per cent of cobalt consumption, 38 per cent of the copper supply and 50 per cent of the consumption of nickel (Wood et al. 2021).

◊ Since 2020, governments around the world have helped to mobilise more than a trillion dollars for energy efficiency-related actions (IEA 2022c). Improving energy efficiency is one of the most cost-effective measures countries can take as it avoids having to install extra generating and transmission capacity which is both mineral-intensive and expensive. The International Energy Agency estimates that previous energy efficiency actions in its 31 member countries reduced energy bills for businesses and households by US$680 billion in 2022 (IEA 2022c).

◊ Resource rich developing countries are increasingly looking to encourage processing within their borders rather than just exporting the (relatively less valuable) raw mineral. The rewards in terms of revenue and jobs can be significant. In the Democratic Republic of the Congo, for example, processing and refining of raw cobalt increased its unit price from US$5.8 to US$16.2 per kilogram (United Nations Trade and Development [UNCTAD] 2023). In 2018, the Rwandan government signed a contract with the United Kingdom-based company Power Resources International Ltd to build the first African coltan (columbite-tantalum) processing/refinery facility.

Barriers

Constructing this energy system needs innovation and investment, to intentionally design a circular, efficient future, ensure equity of access to the benefits of the energy transition and invest in efficiency and circular supply chains at scale. However, there are five challenges that need to be addressed to unlock the potential:

The first is that the policy signals for the energy transition are often unclear. Few countries have dedicated policies for circularity and efficiency in energy transition minerals (Toledano, Bauch and Arnold 2023). Many countries have, for example, set targets for the phase-out of internal combustion engines, but these are rarely accompanied by credible policies to scale up charging infrastructure or support battery supply chains. This leaves businesses uncertain about the levels of future demand for clean energy technologies and reduces incentive to invest in them (ETC 2023a).

The second is that there are a wide variety of regulatory systems between, and even within, countries. This complicates investment in new efficient technologies and circular approaches. In the case of the United States of America, for example, at least 23 states have extended producer responsibility laws for electronic waste, but these laws vary on what is required. This makes collection and participation inconsistent and increases the costs for manufacturers to comply with the regulations (Unites States Government Accountability Office [USGAO] 2022).

The third challenge stems from the complexity and level of maturity of the technologies involved (Toledano, Bauch and Arnold 2023). For example, variations in electric vehicle battery design and complicated battery chemistries mean that different hydrometallurgical or pyrometallurgical techniques are needed. The rapid development of battery technology means that recycling infrastructure is struggling to keep up (ETC 2023a). Meanwhile, many clean energy technologies are difficult to disassemble for recycling or repair. This inhibits reuse and complicates recycling. The costs of transport can also make it economically unviable when the market value of the recovered minerals is low (USGAO 2022).

The fourth issue, which is particularly relevant to recycling and the reuse of clean energy technologies, is that the stock of 'recyclable' or 'reusable' end-of-life products is still a fraction of the overall growing demand for energy transition minerals (Bobba et al. 2018). This will change over time as the current generation of appliances and vehicles reach the end of their life, but most analysts expect that there will not be enough secondary minerals in the system to make a significant dent in primary demand for much of the next decade (ETC 2023a). That said, the collection of many minerals could be ramped up even now (USGAO 2022).

The fifth challenge is that the volatile prices of many of the energy transition minerals weaken the impetus to invest in efficiency, circularity and responsibility. Despite progress in recycling processes and innovation in battery designs, the recycling of lithium-ion batteries is not taking off because of the costs of logistics and the fact that formal recycling infrastructure is not available in many parts of the world (Kendall et al. 2023). Meanwhile, the costs of transport and reprocessing can make recycling economically unviable when the market value of the recovered minerals is low (USGAO 2022).

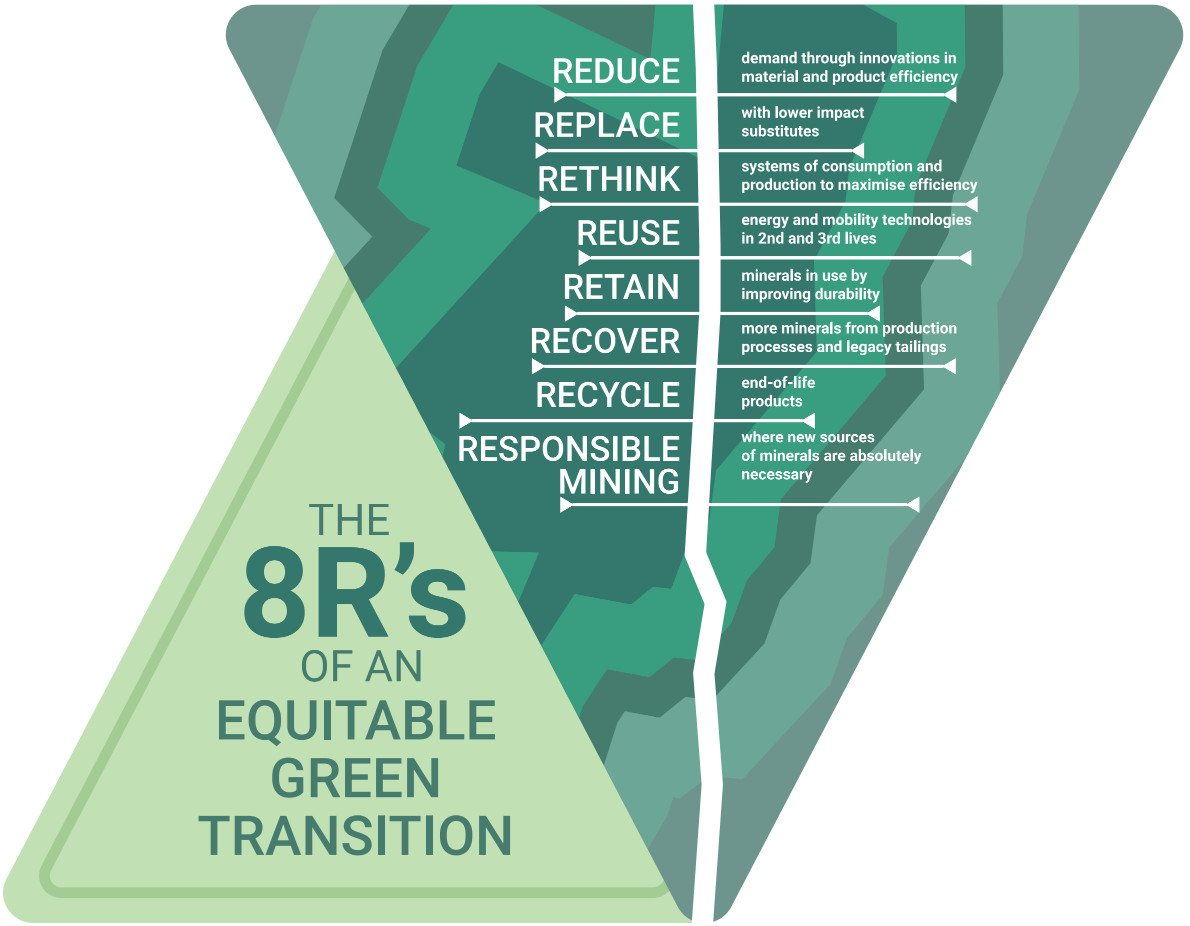


Figure 6: The eight 'R's' that can help to deliver an equitable green transition.

IV. Recommendations

As discussed above, the green transition needs to achieve several features simultaneously and at an almost unprecedented scale. The use of energy transition minerals needs to be more efficient and more circular. Their extraction needs to be done in a more responsible way. And the whole process needs to be equitable within and across countries. This means ensuring that developing countries do not get left behind in the renewable energy technological sprint that is currently taking place, that they can benefit from their own mineral endowments.

But efficiency, circularity responsibility and equity are abstract concepts that can be difficult to apply in practice. So this paper proposes eight 'R's' help to frame how efficiency, circularity and responsibility can be integrated throughout the life cycle of energy transition minerals (Kirchherr, Reikie and Hekkert 2017). The framework then leads to the report's 31 recommendations for immediate action by the international community, national governments, investors and industry. UNEP is actively conducting further research into the Eight R's, with a particular focus on exploring equity issues highlighted throughout the section below, and to understand the different approaches to circularity.

The Eight 'R's'

In essence, governments and the international community should rethink systems of mobility, housing and industry to meet the same human needs with fewer minerals. The world needs to design for a radically more efficient future. This means developing systems that are fundamentally more efficient

and circular, such as expanding access to public transport and shared mobility systems, harnessing nature for cooling in cities by planting trees to reduce the energy requirements for cooling and designing cities where basic needs are easily met. Decentralised renewable energy systems and smart grids reduce the need for electricity to travel long distances, reducing transmission losses. If systems are designed and evaluated by the services they deliver for human well-being, then there is scope for innovative solutions that meet people's needs

with fewer resources (Potocnik and Teixeira 2023). Expanding public transport and shared-car schemes, for example, can provide mobility without multiplying the private car fleet.

Governments and industry need to reduce the meteoric demand for energy transition minerals through improvements to material and energy efficiency. By building collective, larger energy systems we tap into economies of scale that can deliver more energy per kilogramme of energy transition minerals that are used. On a per kilogramme/Megawatt basis, a 3.45 MW turbine contains around 15 per cent less concrete, 50 per cent less copper and 60 per cent less aluminium than a 2 MW turbine (REN21 2023). Smaller cars can reduce demand for energy transition minerals by almost a quarter, potentially reducing metal demand by up to 20 per cent (Potocnik and Teixeira 2023).

If successful, a reduced demand for energy transition minerals could significantly impact the economies of producer countries that heavily rely on mining revenues. Therefore, it is crucial to aim for a gradual rebalancing of mineral consumption, allowing demand to increase slowly over time, thus avoiding sudden fluctuations in prices that could destabilize producer countries' economies.

Developing countries might also struggle to reduce their own need for minerals, due to the high up-front investments and costs of improved efficiency. Therefore, how resource-rich countries will reduce their need for energy transition minerals and how will they benefit from the reduction of global demand are questions that remain front and centre.

Furthermore, focusing solely on mining innovations presents risks. Mining is a lengthy process, and a swift energy transition will require investments in innovations that reduce mineral demand. Diversifying innovations beyond the mining sector—such as in energy storage technologies, recycling systems, and material substitutes—is essential to avoid overreliance on the mining aspect alone and ensure a more sustainable, accelerated transition.

It is possible to replace energy transition minerals for lower impact substitutes where possible. Substituting scarce energy transition minerals with other materials is another way to address supply challenges and reduce the need for virgin mining. For example, graphite need not only be mined. It can also be produced synthetically (albeit through a carbon-intensive process) or substituted with silicon or lithium. This potentially reduces the need for dozens of new graphite mines (ETC 2023a).

Designers and producers of clean energy technologies have to develop ways to retain those minerals in use for longer. Clean energy technologies, and the energy transition minerals included in their construction, have different projected lifespans depending on their nature and use. Most solar panels, for example, have a projected lifespan of 25–30 years before their energy performance degrades to the point that it is more cost-effective to replace them with new panels. Wind turbines, meanwhile, have an average lifespan of around 20–25 years. Finding ways to keep those minerals in the system for longer has a significant impact on the overall amount of energy transition minerals needed.

Extending the lifespan of clean energy technologies would reduce the need for continuous extraction of energy transition minerals, but this relies on the development of new technologies that may not be easily accessible to developing countries. It is crucial to ensure that these countries have access to newly designed, longer-lasting products for their sustainable energy transition. Additionally, care must be taken to avoid supplying developing countries primarily with outdated technologies that are nearing the end of their optimal use, forcing them to operate under suboptimal conditions.

Governments and industry must also find ways to reuse minerals in second and third lives. Once energy transition minerals have been through their initial use they can be repurposed and kept in use. Extending the life phase of renewable energy technologies depends on the technology but, in general, once an electrical vehicle battery is retired from use it can still provide 10–15 years of service as a stationary battery pack (Kendall et al. 2023).

Industry must recover minerals more effectively from production processes and legacy tailings sites. Additional minerals can be recovered by increasing the efficiency of extraction processes, exploiting co-located minerals as secondary products or by re-mining legacy waste sites (tailings dams). Recovery of co-products during the extraction, smelting and refining stages enhances circularity. Capturing these by-products helps to avoid additional waste management and treatment processes and reduces the environmental impacts associated with them (ICMM 2022). Reprocessing of tailings for energy transition minerals recovery helps to reduce the volume of the tailings to be managed as well as the concentration of some potentially toxic elements (such as copper and zinc) (Global Industry Standard on Tailings Management [GISTM] 2020).

While recovering minerals from tailings and improving extraction efficiency can reduce environmental impacts, it is not a process without environmental impacts or financial costs. For this reason, it is important to ensure that resource-rich developing countries have the financial resources to recover tailings in a manner that is environmentally sound, to guarantee effective reclamation of tailings dams sites, to recover minerals sustainably. International support is critical for ensuring that developing countries can participate in and benefit from new recovery practices without being left behind economically or environmentally.

Governments and industry need to recycle end-of-life products into new products rather than send them to landfill. Base metals that are used in large volumes (e.g., nickel, copper, aluminium) achieve high end-of-life (EOL) recycling rates, as do precious metals that attain very high global prices (e.g. gold, platinum and palladium). However, the absolute quantities of energy transition minerals being recycled are low at the moment and will take time to increase (ETC 2023a). That is because a lot of today's minerals are already 'locked up' in products that are still in use. Secondary supply can only be scaled up as clean energy products reach the end of their lifespan (and possibly a second life too), meaning that the lithium, copper, graphite and silicon that is being put into energy infrastructure now will not become available for use for decades (ETC 2023a).

But even with maximum efforts for greater efficiency and circularity, the fast-growing demand for minerals for the green transition means that there will need to be a significant jump in the extraction of energy transition minerals in the coming decades. There are sufficient geological reserves of most energy transition minerals to meet projected demand between now and 2050, even without significant efforts to make their use more efficient and circular (ETC 2023a; ETC 2023b). However, the challenge is how to extract those resources at the scale and pace required while minimizing the serious environmental and social implications of irresponsible mining explored in Chapter 2. Consequently, it is vital that minerals are extracted in a responsible way that is equitable and environmentally sustainable, respectful of human rights, inclusive of artisanal and small-scale miners.

Collectively these Eight R's represent an opportunity to save money, avoid environmental damage, develop value-added processes in producer countries, maximise efficiency, avoid waste and deliver the energy transition.

Policy levers

The world needs to decarbonise fast. It also has to decarbonise equitably. The energy transition is a chance to rewrite the legacy of mining. It is a chance to make equitable energy systems that take a socially informed, conflict-sensitive and ecologically-sound approach towards development and decarbonization. To put it more simply, this means that an electric vehicle can only be 'green' if the minerals that went into it have been produced in a responsible and sustainable manner. It also can only be 'green' if the electricity that powers it constitutes green energy and if it has been designed in such a manner that its constituent parts can be reused or recycled when it reaches its end of life.

Ultimately the transition will only be sustainable if it doesn't come at the expense of other global environmental goals or peoples' health and economic well-being. The scale of the mineral needs for the energy transition under business-as-usual extraction is such that large-scale mining will likely mean creating new environmental and social challenges even as we seek to solve

Box 2: UNEA Resolution 6/5 on the Environmental aspects of Minerals and Metals

The United Nations Environment Assembly at its sixth session in 2024 adopted a resolution entitled "Environmental Aspects of Minerals and Metals" (UNEP/EA.6/Res.5) focusses on improving the environmental aspects of minerals and metals along their full life cycle. The resolution asked UNEP to: "support enhanced cooperation among Member States on policy, technological, technical, and scientific aspects with the aim of strengthening management of environmental aspects of minerals and metals". This resolution built on a previous one (UNEP/EA.5/Res.12) which asked UNEP to: "...convene transparent and inclusive intergovernmental regional consultations ... with the aim of developing non-prescriptive proposals to enhance the environmental sustainability of minerals and metals along their full life cycle, in line with the 2030 Agenda for Sustainable Development." These meetings took place during 2023. The following recommendations also draw on those consultations.

climate challenges. These will not be confined to local mining sites or even to national boundaries. They involve such a complex set of ecological, human, governance and geopolitical risks that will have repercussions on planetary boundaries.

That is not to say that win-win opportunities are not possible. Governments can achieve both development and environmental gains – governments can deploy economic instruments that simultaneously manage environmental risks and support resource-led development strategies. Tools such as variable royalties can be linked to both environmental degradation and the extraction of critical resources, directing revenues toward local development projects, climate adaptation and infrastructure. By integrating these mechanisms, resource extraction becomes a driver of both environmental responsibility and economic resilience. This can be complemented by sovereign wealth funds that capture surplus revenues during high-price cycles, ensuring that public investments remain steady even when mineral prices fall, while still addressing environmental liabilities and fostering long-term economic stability.

Moreover, concession agreements can require companies to contribute a portion of their royalties to these stabilization funds or community development initiatives, ensuring local benefits continue regardless of resource price movements. This way, both environmental restoration and socio-economic development projects remain adequately funded. Performance bonds, meanwhile, guarantee that environmental costs are accounted for upfront, ensuring companies remain financially responsible for rehabilitation even in the face of market downturns. An added advantage is that many governments are already familiar with these instruments and thus there are ample research resources and peer-peer learning opportunities to transfer applications to the context of energy transition minerals,

Decision makers have a number of ‘policy levers’ available to promote investment in circularity, efficiency and responsible mining. These levers will also have the potential ensure equity in the energy transition and to foster innovation for new technologies and processes that minimise the need for energy transition minerals.

Policies can set ambitious targets for efficiency, circularity and energy access. They can build markets for new technologies that are less materially intensive. These targets can be aspirational, but they can also set broad policy direction for investors and planners. For example, the European Union has set a series of targets to encourage increases in its own production of energy transition minerals. It is aiming by 2030 to extract 10 per cent and process 40 per cent of the European Union’s annual consumption. It is also aiming to recycle at least 45 per cent of each of the strategic raw minerals contained in the Union’s waste (Simon 2023).

Many countries could clarify their regulatory frameworks to incentivise greater efficiency, circularity and responsibility. A lack of consistent regulations is slowing innovation and fragmenting the sector (World Circular Economy Forum 2021). For example, complex waste management regulations can discourage recycling, making re-processing of waste streams or tailings at mine sites more common than they ought to be (Toledano, Bauch and Arnold 2023). Meanwhile, an enabling regulatory environment is required to support a gender-just energy transition. Energy policies must address gender-differentiated energy needs, and control over and access to energy resources for equitable access to energy services between women and men (Ngum and Kim 2023).

Harmonised standards for more responsible mining could improve the overall environmental and social performance of mining in countries while helping companies navigate the current jungle of competing standards. Extended producer responsibility (EPR) can encourage accountability, circularity and efficiency by ensuring producers bear extended responsibility for their products, including for the take-back, recycling, and final disposal of products. This type of framework holds producers accountable for the environmental costs

associated with products while indirectly promoting eco-products and designs that return value back to the producer (Young, Laura and Chovan 2021). EPR shifts the responsibility upstream towards the producers and encourages them to take environmental considerations into account when designing their products. (Toledano, Bauch and Arnold 2023).

New incentives are required to help scale up efficiency, circularity and responsible mining. Several rich countries have put sizeable programmes of incentives into place with a view towards encouraging greater energy transition mineral development in their home countries. In the United States of America, the Inflation Reduction Act of 2022 includes electric vehicle tax credits, with domestic production requirements that also include minerals recycled in North America. It also provides some incentives for scaling recycling capacity. The Act established a combination of grants, loans, rebates, incentives and other investments to foster the country’s energy transition by relocating the supply chain of energy transition minerals. Alongside other federal and state programmes, it amounts to a trillion-dollar public investment in the energy transition (ETC 2023a).

This all needs to be combined with improved systems of governance at both national and international levels to support innovation, spread best practices and manage tensions between stakeholders. Energy transition minerals have become a highly contentious issue, but no one country has access to all the energy transition minerals that it needs nor does any one country have the processing capacity to produce them. Hoarding of scarce minerals, overly strict export measures, or making efforts to use mineral reserves or mineral production as levers of influence may deliver short-term geopolitical gain but will likely cause increased tensions.

Greater collaboration is essential to build trust along supply chains that have often become contentious and susceptible to short-term political calculation. This is playing out in the lack of trust between producers and consumers of energy transition minerals. It is simultaneously playing out in communities surrounding mineral extraction sites. Appropriate planning and putting systems in place at multinational levels will enable cooperation, coordination and innovation in the energy transition minerals space. New frameworks of multilateral cooperation are needed to avoid competition over scarce resources leading to geopolitical conflict and/or fuelling internal conflicts in resource-rich countries.

Current international structures are not fit for purpose to deliver on these aims. Various ideas have been proposed. These have included broadening the mandates of the International Energy Agency (IEA) or the International Renewable Energy Agency (IRENA), forging an International Mineral Supply Agreement or even setting up a bespoke agency to create a forum for collaboration, policy alignment, sharing of best practices and so on. Collaboration between stakeholders is critical to overcoming these barriers. This can be achieved through a systematic and integrated approach towards problem solving and value creation throughout the entirety of the value chain (World Circular Economy Forum 2021).

Better coordination, better incentives and better regulatory frameworks will also help to foster the investment needed for a more sustainable, efficient and circular transition. The investment needs for the green transition are huge. The Energy Transitions Commission (2023a) estimates that up to US$1.7 trillion of investment are needed to expand mining, refining and recycling plants. As much as 75 per cent of that investment needs to be mobilised this decade.

Summary

◊ Greater efficiency, circularity and responsibility in the extraction and use of energy transition minerals throughout their life cycle can address three looming challenges with equipping the energy transition: supply shortages of energy transition minerals, time lags in ramping up supply, and the potential environmental and social impacts of a rapid expansion in mining.

◊ Even if maximum efficiency and circularity is achieved, most analysts agree that meeting net zero goals requires tripling in the extraction of energy transition minerals. It is vital that those minerals are extracted in a responsible way that is socially just, that brings benefits and jobs to producing countries and that is environmentally sustainable.

◊ It is essential for us to do 'more with less' and do it better. These are the Eight R's. We need to reduce the meteoric demand for energy transition minerals through improvements to material and energy efficiency. We should rethink systems of mobility, housing and industry to meet the same human needs with fewer minerals. We must replace energy transition minerals for lower impact substitutes where possible. We have to retain those minerals in use for longer while finding ways to reuse them in second and third lives. We must recover minerals more effectively from production processes and legacy tailings sites. We need to recycle them into new products rather than send them to landfill. Finally, it is vital that those minerals that do need to be extracted are extracted in a responsible way that is socially just and environmentally sustainable.

◊ Delivering these critical transitions requires coherent policies supported by effective regulatory frameworks, effective incentives and standards that are applied throughout the supply chain, supported improved governance and collaboration at both national and international levels.

Postscript: Modelling the Policy Options

This Working Paper has provided a conceptual frame and explored the various policy levers that could simultaneously deliver greater efficiency, circularity and responsibility, while also ensuring equity in the division of the costs and benefits of the energy transition. This publication presented recommendations that outline the 8Rs an initial framework designed to integrate efficiency, circularity and responsibility across the life cycle of minerals essential for the energy transition.

UNEP will continue to develop the themes and seek answers to the following questions in future publications:

◊ In the process of rethinking systems, resource-rich countries might struggle to maintain mining at the same scale. Will this mean resource-rich countries will lose out, or can they benefit from this process by creating faster job and investment opportunities from emerging industries, while maintaining some mining operations? In other words, how to ensure equity for lower income, resource rich countries while pursuing enhanced circularity? What are the potential upside gains for lower income, resource rich countries?

◊ As we reduce demand for critical energy transition minerals grows high up-front costs of improved efficiency can be a barrier for developing countries. Thus, how will resource-rich countries reduce their need for energy transition minerals, and also how will these countries benefit from the reduction of global demand? What are the global and regional distributions of costs and benefits associated with a circularity-equity-responsibility approach?

◊ As countries embark on recovering minerals from tailings, how can resource-rich developing countries ensure having the financial resources to recover tailings in a manner that is environmentally sound and guarantees effective recovery of tailings dams? Furthermore, what mechanisms can be put in place to ensure that developing nations have the financial and technological support to enable them to recover minerals sustainably? In particular, how to balance sustainability concerns when assessing options for re-mining of tailings and other mine waste?

◊ Recycling materials, requires investments and technology that are seldom available to developing countries. Would resource-rich countries lose revenue if primary mining decreased? What advantages can producer countries derive from a recycling economy? What are the investments and opportunities that would need to be made available to guarantee that developing countries are not left behind when recycling increases and primary mining starts to slow down? What is the potential for regional risk pooling for smoothing public investment and mineral price volatility?

◊ As for responsible mining, how can we reduce impacts given the existence of multiple mining standards, especially since higher standards may be seen by some resource-rich regions as making mining agreements even more complex than they already are? Additionally, could more ambitious and responsible mining practices open new market opportunities for producer countries? And what actions would be required from the demand-side actors to support this shift?

This working paper serves as a starting point for formulating a circular economy approach to mining of critical energy transition minerals, and ensuring this approach is based on the principles of equality and responsible mining.

In future publications, UNEP will present the results of a quantitative analysis of the differing impacts these policy levers might have to achieve these aims. Upcoming publications will also strive to explore the potential dividends and benefits of pursuing actionable recommendation four—of increasing circularity—of the UN Secretary General's Panel on Critical Energy Transition Minerals.

ACTION RECOMMENDATIONS BASED ON THE 8R's MODEL

	Timeframe	Reduce	Replace	Rethink	Reuse	Retain	Recover	Recycle	Responsible Mining
International Community									
Promote the transparent sharing of data and innovations on efficiency and circularity, e.g. set up publicly available material registries; encourage the sharing of information of promising technologies.	Short term - long term	◆				◆	◆	◆	
Develop monitoring systems to track innovations towards efficiency and circularity and their impact on mineral demand, including through digital 'passports' for renewable energy technologies that provide transparency about mineral life cycle impacts.					◆	◆			
Develop global standards and ambitious targets for secondary minerals and metals, develop and harmonise definitions of remanufactured goods, used goods and goods produced using circular processes.	Short term - long term				◆	◆	◆	◆	
Agree ambitious global targets for energy transition mineral efficiency in renewable energy systems and for better durability and repairability of clean energy technologies, including through extended producer responsibility	Short term - long term	◆			◆	◆			
Facilitate international negotiations to improve cooperation over circular approaches to the energy transition, including through eliminating tariff and non-tariff barriers to trade in circular economy goods and services, including second-life products, goods for refurbishment and remanufacturing, waste and scrap for recovery, secondary raw materials.	Short term				◆				
Encourage 'system-wide' research and development that looks at the scope for efficiency and circularity within and across sectors including urban planning and transport services.	Short term - long term	◆		◆		◆			
Develop legislative guides for implementing a circular economy and support countries with implementing those plans.	Short term	◆				◆			
Facilitate technology transfer and industrial cooperation that enables countries to access alternative material technologies and to facilitate 'industrial symbiosis', enabling one industry's waste product to become another industry's raw material.	Medium term - long term		◆				◆		
Conduct a global assessment of environmental aspects of minerals and metals management and particularly governance gaps of relevant instruments, including standards, in cooperation with Multilateral Environment Agreements (MEAs) and other stakeholders (UNEA 5/12 consultations).	Short term								◆
Advocate for improved standards and targets for responsible mining. For example, mining that meets high environmental, social and governance standards should be included in the list of sectors in financial taxonomies (such as that of the European Union) that qualify for "sustainable finance".	Short term - long term								◆
Encourage countries and strengthen regional and national capacity to establish sovereign wealth funds to capture surplus revenues from mineral extraction, ensuring long-term funding for infrastructure, climate adaptation, and sustainable development projects, thereby stabilizing revenue streams over the long term.	Short term - long term			◆					◆
National governments									
Incorporate global standards for material efficiency and energy efficiency into domestic law, e.g. require and promote designs that enable reuse, repairability and recyclability (e.g. no hazardous materials, modular design etc).	Medium term - long term	◆			◆	◆		◆	
Develop circularity and efficiency roadmaps for each industrial sector from the extraction of resources to the end-of-life stage.	Short term	◆			◆	◆	◆		
Set ambitious targets for secondary minerals, metals and by-products, ensure their reuse and recovery across industries and facilitate business-to-business partnerships to enable second and third lives for products using energy transition minerals.	Short term				◆		◆		
Finance research and development into material efficiency and energy efficiency. Investigate mechanisms for advanced market commitments that can facilitate early-stage deployment of new, more efficient technologies.	Medium term - long term	◆	◆						
Require labelling and information on the durability, recyclability and repairability of products in digital product passports.	Short term - long term				◆				
Encourage 'right sizing' through taxation, quotas, standards and awareness campaigns to discourage inefficient uses of energy transition minerals: e.g. taxation on SUVs over a certain weight will encourage better material efficiency.	Short term - long term	◆		◆					
Incentivise, through tax, subsidies or regulation, the reprocessing of valuable waste above alternative treatment methods of waste, such as incineration or landfill.	Short term - long term						◆		
Facilitate service and leasing models, e.g. through designing regulation and incentive systems that can expand public transport and car sharing schemes.	Short term - long term			◆					
Investigate mechanisms for advanced market commitments that can facilitate early-stage deployment of alternative materials where appropriate.	Short term - long term		◆						
Invest in the infrastructure (e.g. collection and processing facilities) for recycling and set industry-specific collection rate targets with increasing levels of ambition.	Short term - long term							◆	
Revisit the national policy framework for mining to ensure there are robust regulations and protections for workers, communities and the environment. Support mineral-rich developing countries through international cooperation to build the necessary institutions and capacities to regulate and enforce responsible mining.	Short term - long term								◆
Strengthen the collection of data, and ensure transparency of information and free, prior and informed consent from affected communities. Mandate the implementation of grievance mechanisms by the industry.	Short term								◆
Implement dynamic royalty systems that adjust based on market conditions and environmental impacts, ensuring a more stable revenue base while discouraging unsustainable extraction. These royalties should fund both local development projects and climate mitigation efforts, smoothing the economic impact of price swings.	Short term - Medium term								
Enforce the use of performance bonds to ensure that extractive industries are held financially responsible for environmental restoration and social obligations. The bonds should cover both ecosystem rehabilitation and community development, ensuring that extraction benefits are shared locally.	Short term - Medium term								
Ensure that part of the financial proceeds from extraction is directly reinvested into local development through concession agreements that mandate investment in infrastructure, renewable energy, or public services in affected regions.	Medium term - long term								
Investors and industry									
Appoint a Chief Circularity/ Efficiency Officer (or focal point) to be responsible for increasing efficiency and circularity in mining, processing and production operations.	Short term - long term	◆	◆				◆	◆	
Work with national governments and the international community to set and exceed standards and targets for material and energy efficiency.	Short term - long term	◆							
Implement trackable material and energy efficiency standards throughout the supply chains of energy transition minerals.	Short term - long term	◆							
Explore 'service' business models where the services that the energy transition minerals provide are sold and the minerals are retained by the business to incentivise circularity and efficiency.	Short term - long term	◆		◆	◆				
Invest in designs that facilitate the reuse of products in second lives, e.g. investigate options for electric vehicle battery design that permits a second life in static energy storage systems; design products with the full life cycle in mind (i.e. easy disassembly for recycling etc).	Short term - long term				◆			◆	
Implement the Global Industry Standard for Tailings Management (GISTM), which, seeks to raise awareness of the social, environmental and local economic context of existing and planned tailings facilities.	Short term - long term						◆		
Invest in research and development to investigate and scale low-impact alternatives to energy transition minerals in short supply or with high social and environmental impacts.	Short term - long term	◆	◆						
Develop partnerships across sectors to share best practice.	Short term	◆	◆	◆	◆				
Invest in avoiding, minimizing and managing the negative environmental and social costs of mining.	Short term - long term								◆

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Annex

Transition mineral extraction and processing

Transition mineral	Extraction	Processing
Aluminium	Primarily sourced from bauxite, a clay-like rock found in a belt around the equator.	Alumina is separated from the bauxite with a hot solution of caustic soda and lime, then heated, filtered, and refined into aluminium.
Boron	Sourced from borax deposits in underground or open-pit mines.	The mined ore is crushed and purified before further chemical processing to produce boron or boron-containing compounds.
Cadmium	Occurs as a minor component in most zinc ores, and to a lesser extent, lead and copper deposits.	Produced as a by-product of mining, smelting and refining of zinc (distilled as cadmium vapour during smelting and then further purified).
Chromium	Primarily found in chromite ores accessed through both open pit and underground mining.	The ore goes through beneficiation to remove impurities, smelted and then further refined. The resulting material is often alloyed with other metals.
Cobalt	Most produced as a by-product of copper or nickel mining in open-pit or underground mines. It is also mined directly by artisanal miners in the DRC	The ore is crushed, ground, and further purified through froth flotation. The concentrate is then further processed through smelting and/ or electrolysis to increase its purity.
Copper	Primarily found in low-grade ores containing copper sulphide minerals in open-pit or underground mines.	The ore is crushed, ground, and purified through froth flotation. The concentrated copper ore is then further processed through smelting and electrorefining.
Gallium	Gallium production is largely dependent on the refinement of aluminum and zinc from bauxite and sphalerite deposits, respectively.	90 per cent of gallium is produced as a by-product of aluminum production.
Germanium	Most germanium production is a by-product of zinc production and from coal fly ash.	The ore is concentrated through crushing, grinding and flotation, then smelted and further purified before being grown into crystals of pure germanium.
Gold	Gold is extracted in a number of different ways: underground and open-pit mines to extract gold bearing ores, to alluvial and placer mining which separates gold particles from lighter materials.	Gold is processed in a number of ways depending on its form and purity. Alluvial deposits can be gravity separated, smelted and refined to increase purity. Mercury is often used by artisanal miners to create a gold amalgam. Low-grade ores are subjected to cyanide heap leaching to dissolve out gold.
Graphite	Natural graphite is mined from open-pit and underground mines. Synthetic graphite can also be produced using industrial processes.	The mined ore is crushed and ground into a fine powder, separated through froth flotation, concentrated, purified, sized, and dried.
Indium	Typically found alongside other metals, primarily zinc.	Indium is obtained as a by-product of zinc, tin, and copper production.
Lead	Typically extracted from underground mines. More than 60 minerals contain some form of lead, but only three are commonly mined for lead: galena, cerussite and anglesite or produced as a by-product of zinc or silver mining.	Crushed and concentrated through gravity separation in flotation tanks, filtered, the resulting ore is roasted, then heated in a blast furnace and further refined.
Lithium	Mostly extracted from brine reservoirs located underground salt-flats or from hard rock mining of mineral ores such as spodumene.	Brines are concentrated through solar evaporation before conversion through a series of chemical processes into lithium carbonate.
Manganese	Over 460 known minerals contain manganese. Sourced from open pit mines and potentially from deep sea mining.	Smelted to produce ferromanganese, which is reduced with carbon to produce the metal.
Molybdenum	Extracted from open-pit or underground mines.	The ore is crushed, ground and purified through flotation processes, using a variety of reagents.
Nickel	Lateritic nickel deposits are extracted from open pits through strip mining. Sulfide nickel ore deposits are extracted from underground mines.	The ore is crushed, and put through separation and chemical processing to refine concentrates which are then smelted.
Platinum Group Metals (PGMs)	PGMs include palladium, platinum, iridium, osmium, rhodium, and ruthenium. PGMs are typically mined underground. They can also be produced as a by-product of nickel mining.	The ore is crushed, and treated through froth flotation to produce a concentrate which is dried and then smelted.
Rare earth elements (REEs)	There are more than 200 minerals which contain various combinations of the 17 REEs .These are typically extracted from open pit mines.	Once crushed, REE minerals can be concentrated in several different ways depending on the particular mineral sought: froth flotation, magnetic separation, electrostatic separation, and heap leaching.
Silicon	The source of silicon is silica in various natural forms, such as quartzite or sand.	The crushed and ground silicon is washed and melted in a furnace.
Silver	Silver, which is generally found in combination with copper-, zinc- or lead-bearing ores, is mined from open-pit and underground mines.	The ore is crushed and ground, separated by froth flotation or other physical and chemical processes, depending on the ore in which it is present.
Tellurium	Typically extracted as a by-product of copper mining.	Tellurium is most often mined by processing the electrolyte sludges from copper mining.
Tin	Found in an ore called cassiterite which is extracted by underground mining, or surface mining from open-pits or gravel pumping.	Smelted and refined to drive off impurities.
Titanium	Found in minerals such as rutile or ilmenite which are typically extracted with dredges in open-pit mines.	Rutile is treated with chlorine gas and then with magnesium or sodium to make a titanium metallic sponge which then undergoes an alloying and metalling process.
Vanadium	Vanadium-bearing ore is extracted through underground or open-pit mining.	The ore is crushed, milled and beneficiated to concentrate the vanadium bearing magnetite ore and then roasted, leached and purified.
Zinc	Most zinc is extracted from underground mines.	The ore is concentrated through crushing, milling and froth flotation before further refined through electrolysis or smelting.
Zirconium	Surface mining – placer deposits in heavy mineral sands. Possible offshore potential. By- product of open pit mining of ilmenite and rutile.	Heavy mineral sands are processed to separate each heavy mineral by weight and magnetism.

[2] These include the US List of Critical Minerals (United States Department of the Interior 2022), the EU Critical Raw Materials Act in parallel with the EU Net Zero Industry Act, the Australian Critical Minerals Strategy (Australia Department of Industry Trade and Resources 2022), and the Canadian Critical Minerals List (Natural Resources Canada 2021). These lists are frequently accompanied by corporate financial incentives, intended to strengthen national or regional supply sufficiency. In the case of the US, it is the Inflation Reduction Act of 2022; in Canada there is the critical minerals exploration tax credit (CMETC) that will offer a 30 per cent tax credit to qualifying exploration expenses (Suarez 2022). The US Critical Minerals List (CML) came into being pursuant to Presidential Executive Order 13817 (EO 13817 2117) and defines a "critical mineral" as one that meets three criteria: (1) it must be a non-fuel mineral or mineral material that is deemed to be essential to the economic and national security of the United States; (2) its supply chain must be vulnerable to disruption; and (3) it must serve an essential function in product manufacture, so that its absence would entail significant consequences for the US economy or national security (EO 13817 2117, s. 2). Such supply chain disruptions could arise for a variety of reasons, including "natural disasters, labor strife, trade disputes, resource nationalism, and conflict." (Hammarstrom et al. 2022, p. ii). It bears pointing out that in determining criticality, factors beyond net import reliance were considered, to include also indirect trade reliance (obscure country of origin), embedded trade reliance (commodity forms part of an imported product), as well as foreign ownership of mineral assets and processing facilities.

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