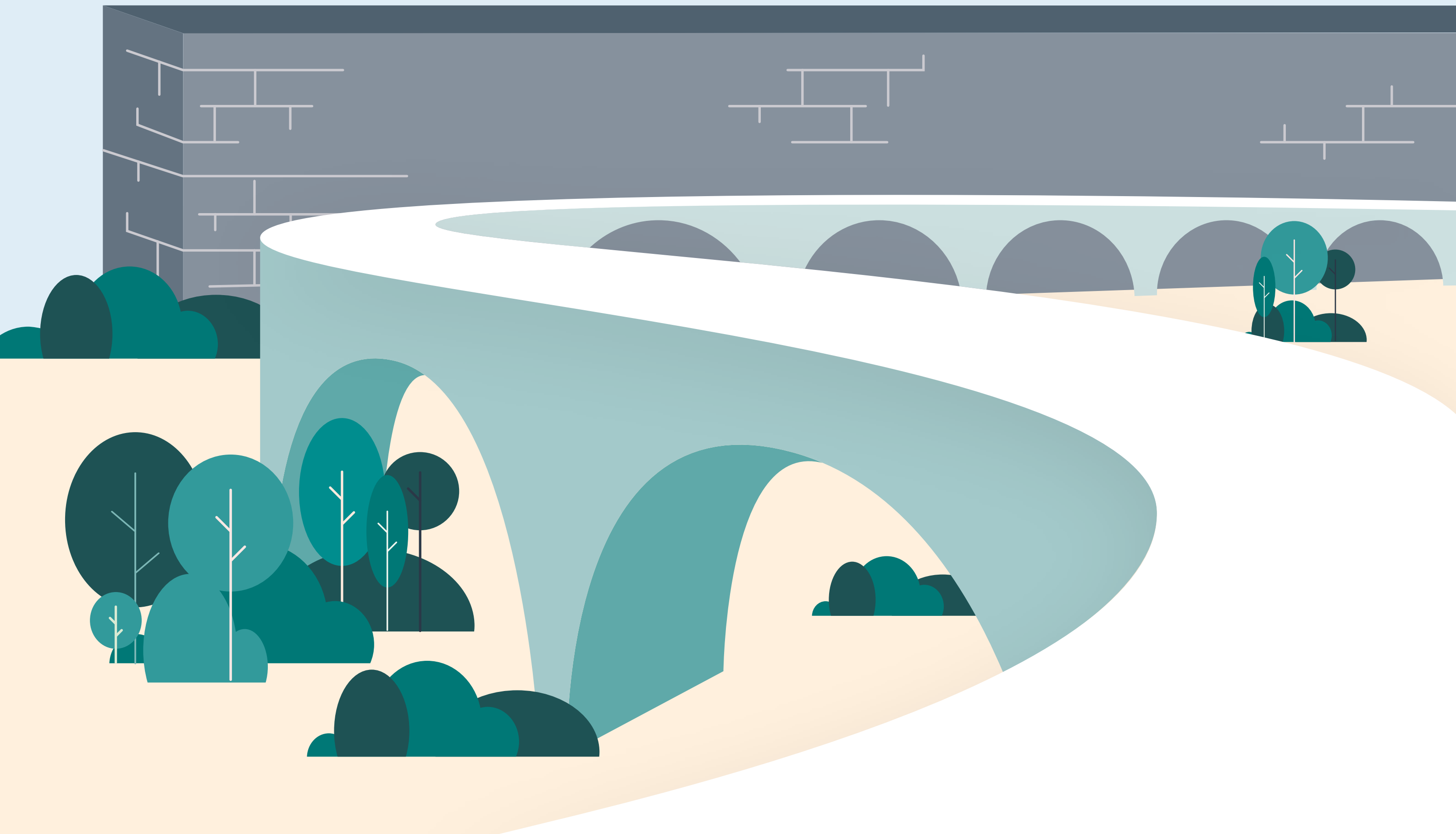
2023

Energy Perspectives

Critical minerals in the energy transition



Speed read

- The role of critical minerals in the energy transition is receiving substantial attention as unprecedented demand, declining reserves and increasingly complex supply chains are likely to result in supply bottlenecks with the potential to delay the energy transition.
- The production, processing and refinement of critical minerals are geographically concentrated, which makes value chains vulnerable to regulatory changes, trade restrictions and political instability. China dominates the supply chains, and any further escalation of geopolitical rivalry could put access to minerals at risk.
- Russia's invasion of Ukraine has added extra pressure on mineral supply and prices as both countries are home to substantial amounts of reserves. Russian supply of grade 1 nickel, palladium and enriched uranium, in particular, is essential to the energy transition.
- The mining and processing of many critical minerals are linked with poor environmental, social and governance (ESG) standards. Governments and corporations face increased regulatory, ethical and reputational risks as ESG issues are under increasing scrutiny.
- Long lead times for new mining projects impact the future availability of minerals, and governments will have to speed up permitting processes to attract the investments needed to support their energy transition ambitions.
- R&D spending on energy technology is on the rise and innovative technology solutions with lower environmental impact and mineral intensities are emerging as a result. Continued focus and spending on R&D will help balance mineral supply and demand and keep the energy transition on track.

Introduction

The energy transition will require such large amounts of metals and minerals that current supply chains need to be extended and/or new ones added at a large scale. Clean technologies such as solar PV, wind turbines and electric vehicles generally require more minerals to build than their fossil-based counterparts. For example, a typical electric car requires six times the mineral input of a conventional car, and an onshore wind plant requires nine times more mineral resources than a gas-fired power plant per unit of output (IEA, 2021). As the global share of wind and solar PV in the energy mix has grown, the average amount of minerals needed for a new unit of power generation capacity has increased by 50% since 2010 (IEA, 2021). The surge in demand means that the reliability and sustainability of mineral resources and supply chains to support the energy transition is an area of increasing interest and importance.

This note provides a high-level summary of some of the key issues surrounding the current and future supply of several critical minerals needed in the energy transition.

Growth in demand for selected minerals from clean energy technologies, 2040 relative to 2020
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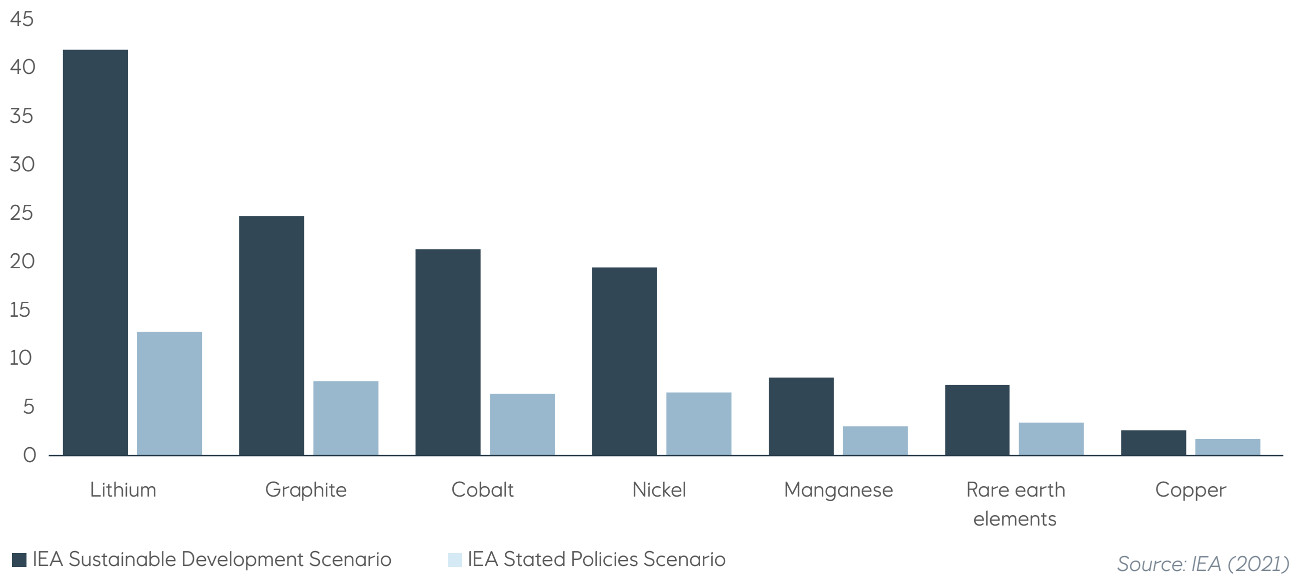
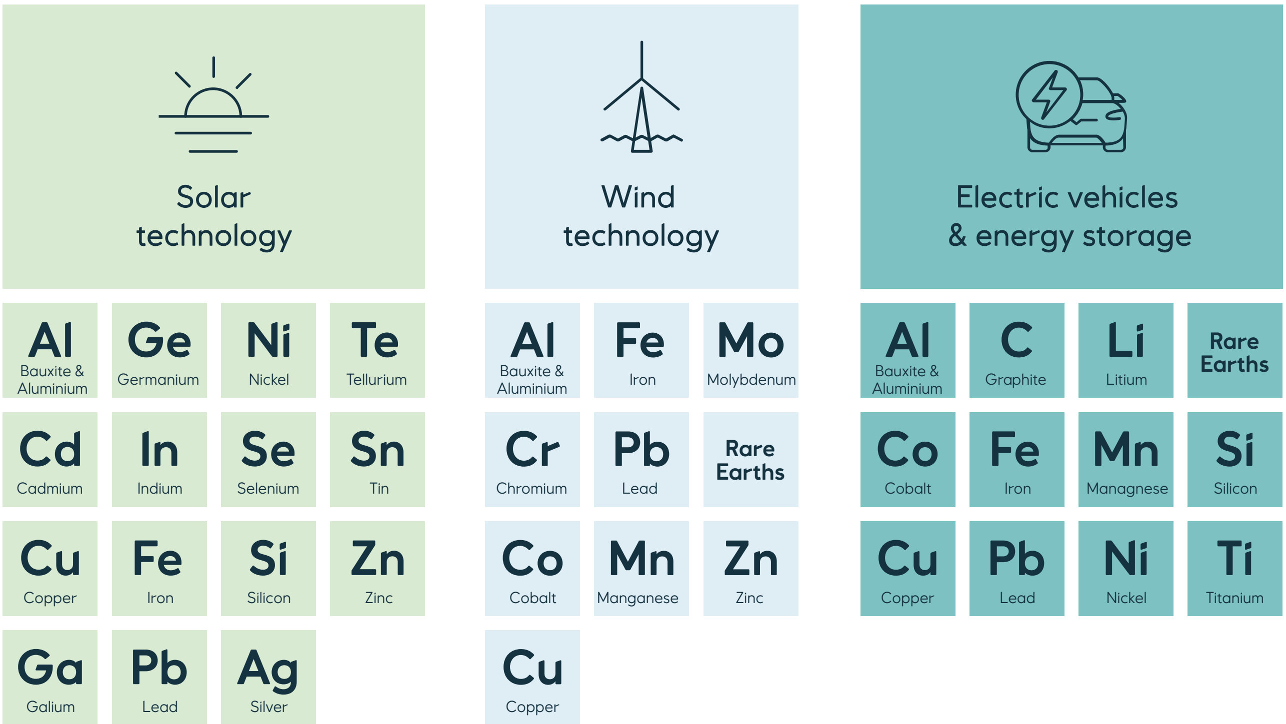


Source: IEA (2021)

Critical minerals needed in clean energy technologies

The list of minerals needed in the energy transition is long (see e.g. IEA, 2021; Hund et al, 2020; Church & Crawford, 2018) and includes copper, nickel, cobalt, lithium, silicon, silver and rare earth elements (REEs) described in more detail below. Those minerals that are deemed essential to national security and economic development and whose supply may be disrupted are classed as critical (Burton, 2022; Schultz et al., 2017). These may vary between regions and change through time.



Source: Modified from Church & Crawford (2018)

Copper is particularly essential to the expansion of electrical networks. The near-term availability of copper supply, of which 40% currently comes from Chile and Peru, has been boosted by recent investments (IEA, 2021). However, copper ore quality and reserves are in decline and only a fraction of global resources are economically viable with present-day technology and processes (IEA, 2021). Copper is not included on the USGS's (United States Geological Survey) list of the top fifty most critical minerals (Burton, 2022), but others, including the IEA and the World Bank, regard it as critical. There are also strong calls from the Copper Development Association (Bhutada, 2023) to elevate its status and for the USGS to include it on future lists to allow for streamlined regulations and faster development of new supply sources to meet future demand.

Nickel, lithium and cobalt are all classed as critical by the USGS (Burton, 2022) and are essential to modern battery performance and continued growth in the electric vehicle market share. They allow modern batteries to deliver higher energy density, greater storage capacity and the ability to recharge repeatedly without efficiency loss (IEA, 2021). Whilst class 2 nickel used in steel manufacturing continues to be available, the supply of class 1 battery-grade nickel is likely to be outpaced by demand in the near term (IEA, 2021). High-pressure acid leaching (HPAL) may provide a new way of producing class 1 nickel from laterite deposits (IEA, 2021) and help sustain production from the world's current leading producers: Indonesia and the Philippines. Lithium production has recently been expanding in the key producing regions of South America and Australia, securing supply in the short term, but new technologies for lithium production are needed to widen the reserve pool in the future. The output from existing and planned cobalt mines, mainly concentrated in the Democratic Republic of Congo, is expected to keep pace with demand in the near term. However, with a sizeable proportion of cobalt being a by-product of copper and nickel mining, the future availability of cobalt will be closely linked to the availability and mining of those products (IEA, 2021).

Silicon and **silver** are essential to the expansion of solar PV capacity, but neither is currently included on the USGS's list of the top 50 most critical minerals (Burton, 2022). Silicon production is dominated by China, whilst silver production and reserves are centred in South America. Crystalline silicon (c-Si) is the most dominant solar PV panel type today and innovation over the past decades has significantly improved mineral intensities. Silicon usage has been reduced in line with a reduction in wafer thickness of panels (Frauenhofer ISE, 2020) and is expected to reduce by a further 25-30% over the next 10 years (ITRPV, 2023). Silver usage in c-Si technology was reduced by >60% between 2010 and 2020 and the trend is set to continue, with a further 35% reduction in usage expected over the next decade (ITRPV, 2023; IEA, 2021).

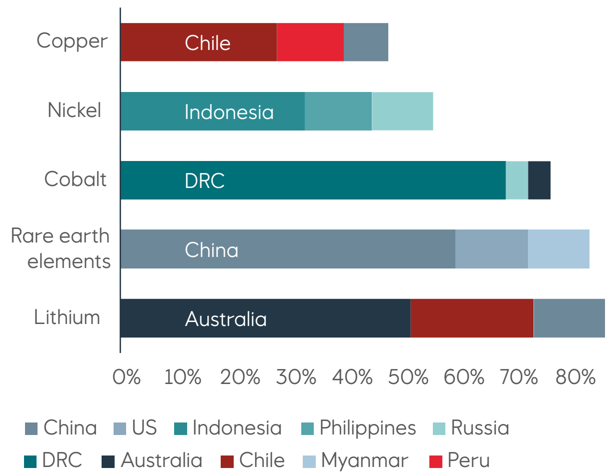
REEs also feature prominently on the critical minerals list published by the USGS (Burton, 2022). Neodymium and dysprosium are crucial to the production of high-strength permanent magnets used in wind turbines and EV motors as they enable a high power-to-weight ratio (Burton, 2022; Haxel et al, 2002). Tellurium is a rare earth element used in thin film Cadmium-Telluride (CdTe) solar cells (IEA, 2021). CdTe solar panels do not require silicon or silver and are therefore cheaper than the more traditional c-Si solar panels. With solar capacity on the rise and CdTe technology expected to gain market share, tellurium demand is likely to increase in the years to come. The wind turbine, solar PV and EV industries are in fierce competition with other industries for reserves (Hurst, 2010; Haxel et al., 2002, King). The tech industry's demand for REEs for use in computers and mobile phones, for example, has exploded in recent years. REEs also have wide applications as catalysts and in military applications such as precision-guided missiles and drones. Whilst REEs are not actually as 'rare' as the name suggests, finding concentrations that are economical to extract in an environmentally sustainable way is a challenge. China currently dominates the REE value chain from production through processing and refinement, but with Vietnam and Brazil each holding approximately 20% of global REE reserves and producing almost nothing (LePan, 2021), there may be options for future supply chain diversification.

China dominates the supply of minerals needed in the energy transition

The current geographic concentration of production, processing and refinement of critical minerals is a considerable challenge to the security of supply of these commodities (IEA, 2021). Production of energy transition-relevant minerals is more geographically concentrated than that of oil and gas, with the three top producers accounting for 50-90% depending on the mineral. More critically, China completely dominates processing and refinement and hence the supply of some of the most critical energy transition minerals. China controls nearly 60% of global lithium processing and 40% of copper processing, as well as 85-90% of the processing operations that turn REEs into metals and magnets. China also processes the most nickel (35%), whilst Indonesia, the world's leading producer of nickel with a 30% share of global production, has a 15% processing share. Cobalt production relies almost exclusively on the Democratic Republic of Congo. However, processing is again controlled by China with a 65% market share.

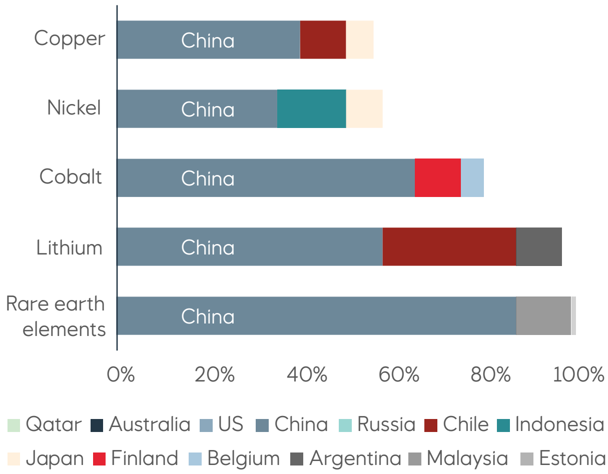
Geographical concentration makes value chains vulnerable to regulatory changes, trade restrictions and political instability. China's dominance is of particular concern, especially given the current US-China rivalry, and there are recurring rumours that China is considering limiting exports of REEs (e.g. Tabeta, 2023; Yu & Sevastopulo, 2021) of which the US and EU are large consumers. However, if it comes to a weaponisation of REEs, that could lead to an acceleration in production outside China and in turn, undermine China's dominance in the industry. That happened after China put export restrictions in place in 2010 and most likely contributed towards a reduction in China's REE production share from >90% in 2010 to <70% in 2020 (IEA, 2021; LePan, 2021; King). Also, the phenomenal growth in the demand for minerals that the energy transition presupposes, can in any case hardly be met by any single country or producer alone, especially since China is approaching its limits in terms of low-cost supply of labour and capital-intensive manufacturing capacity.

Percentage share of top three mineral extracting countries, 2019



Source: IEA (2021)

Percentage share of top three mineral processing countries, 2019



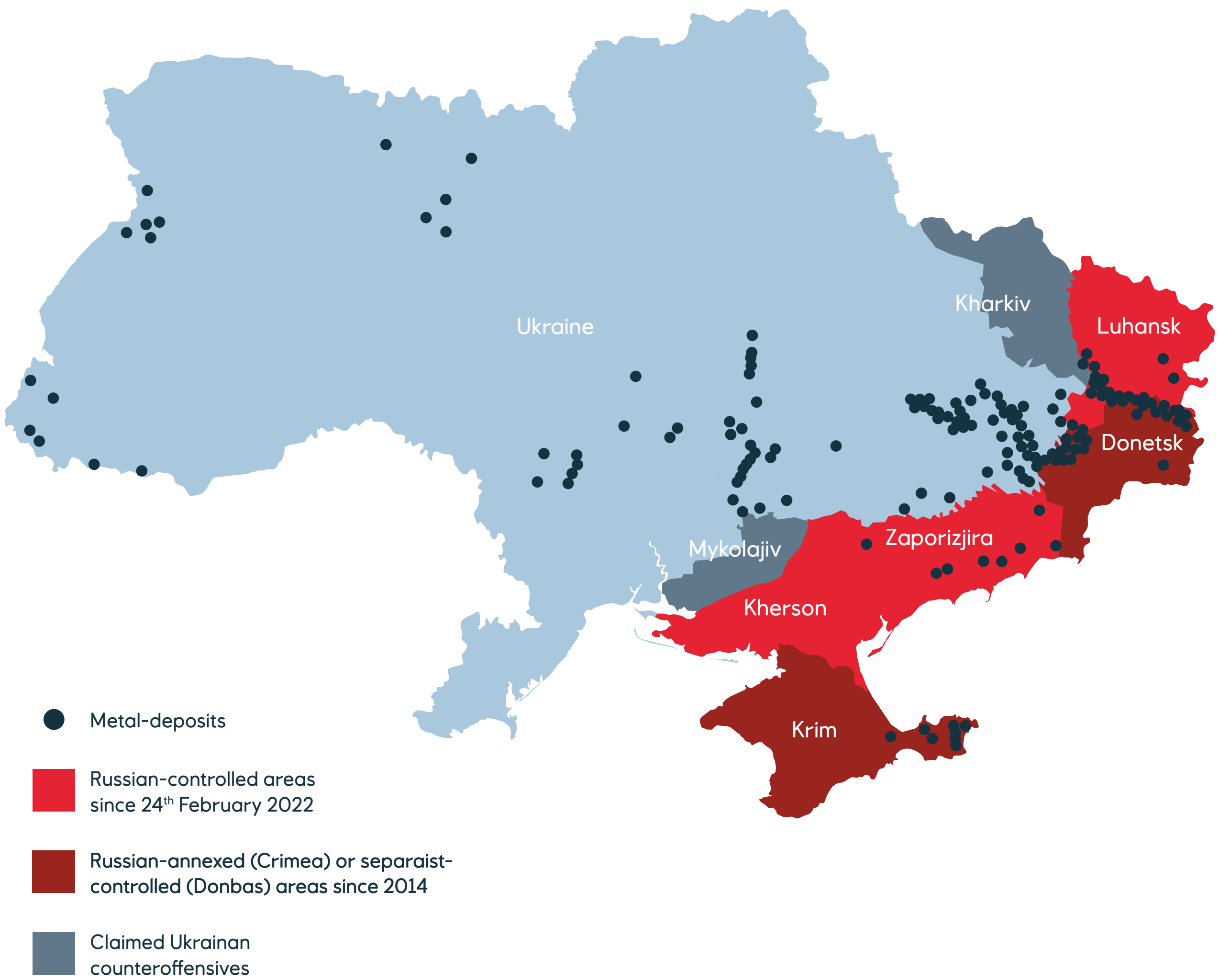
Source: IEA (2021)

The Russian invasion of Ukraine and its implications for critical mineral supply

Russia is a major producer of many minerals and metals that are vital for the clean energy transition. Bans on Russian exports in response to sanctions following Russia's invasion of Ukraine have impacted supply and put significant pressure on mineral prices in already tight markets (OECD, 2022). Ukraine is a natural resource superpower and possesses 117 of the 120 most widely used minerals and metals, including 40 needed for the energy transition (Faioila & Bennett, 2022). Approximately 20% of the country's resources are in territories occupied by Russia (Faioila & Bennett, 2022).

The supply of raw materials endangered by Russia's invasion of Ukraine includes class 1 nickel (needed for batteries) and platinum (needed for hydrogen electrolysers) of which Russia controls 17% and 14% of global production, respectively. However, more critically, Russia's production of palladium (used in catalytic converters to reduce emissions) and enriched uranium (used in nuclear technologies) both amount to more than 40% of global production and hence any long-term disruptions to supply could have significant implications for the energy transition (IEA, 2022a).

Location of Ukrainian metal deposits and areas under Russian control*



Source: Modified from Faiola & Bennett (2022) and Hird et al. (2023)

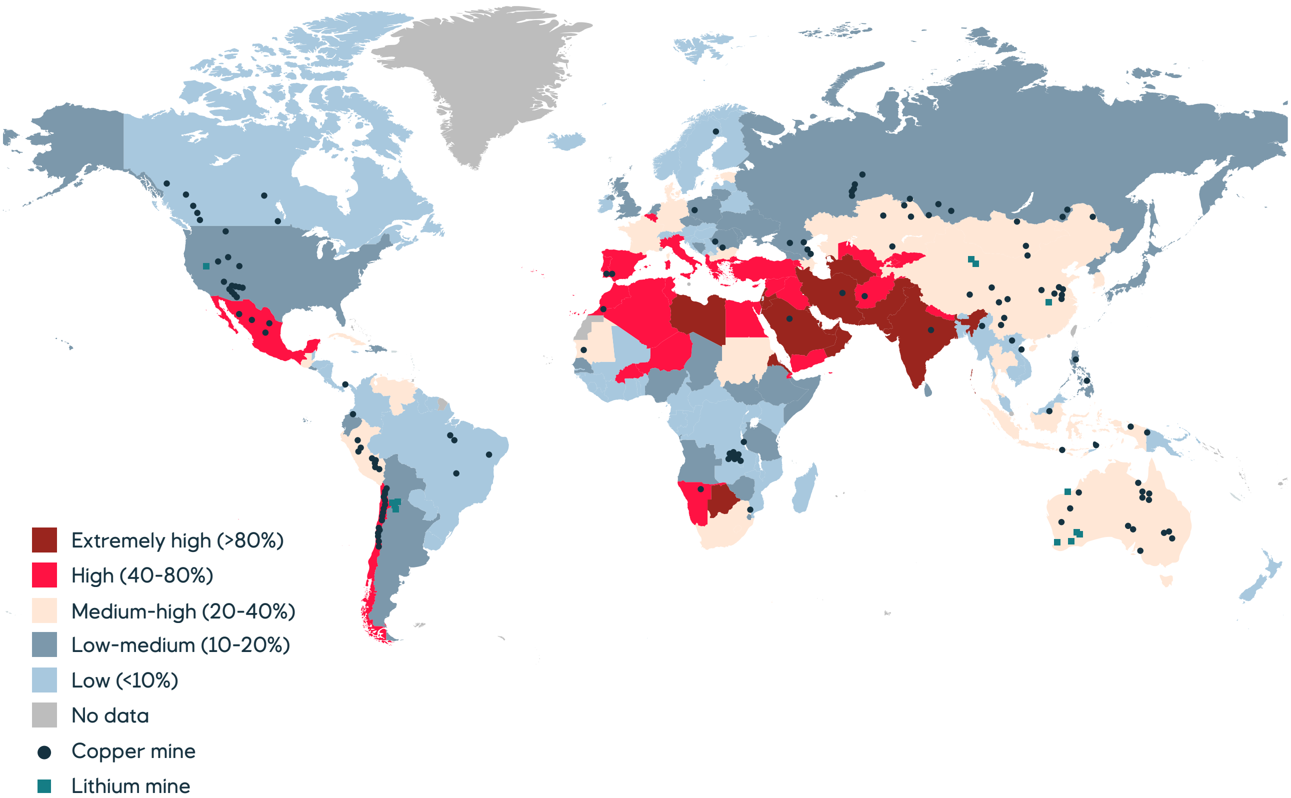
**Map represents situation reported on 10th May 2023 (Hird et al., 2023)*

The list of challenges impacting mineral supply is long

The access to future minerals globally is by no means limited only by reserve constraints and geopolitics, but by a far wider spanning set of potential bottlenecks. These exist throughout the complex supply chains from extraction, through refinement to the final products and range from access to refining chemicals, through water shortages, human rights, and volatile commodity prices, to name a few.

Environmental, social and governance (ESG) issues pose significant challenges to the stable sourcing of minerals (IEA, 2021). Growing demand for minerals will increase the need for new mines as well as expand and extend already existing projects, impacting land use, biodiversity and communities. The amount of CO2 emissions related to mining operations is another concern, with many of the minerals needed for the energy transition having extremely high energy input requirements and CO2 intensities. Water shortage is yet another concern as mineral extraction and initial processing require substantial amounts of water and hence may locally be in competition with other uses such as farming. Around 50% of lithium and copper production is concentrated in areas of already high water stress in South America and Australia (IEA, 2021), and future increases in demand will exacerbate the problem. Moreover, increased mineral demand combined with declining ore quality (e.g. copper ore) will lead to an increase in mining waste in the form of tailings, waste rocks and hazardous waste such as heavy metals, radioactive material and harmful chemicals, increasing the risk of land and groundwater contamination (IEA, 2021).

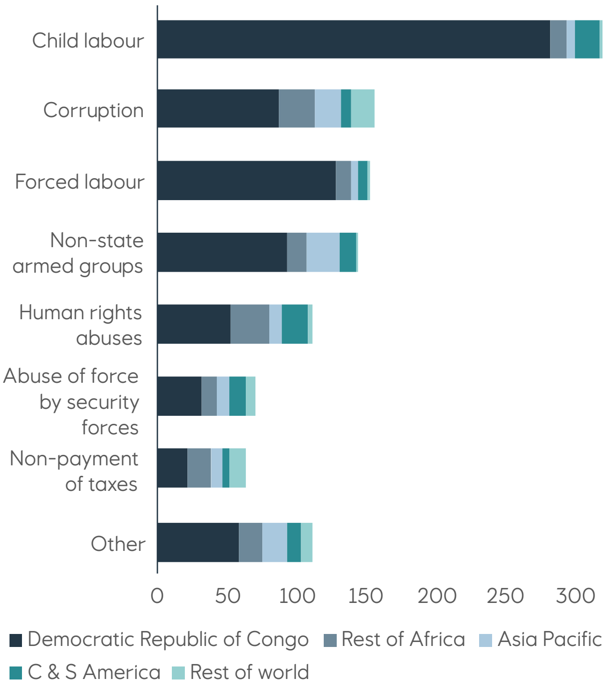
Location of copper and lithium mines and water stress levels, 2020



Source: Modified from IEA (2021), World Research Institute (WRI) Aqueduct 3.0 database, MapChart

Social and governance issues related to mineral extraction also include human rights violations, child and forced labour, health and safety concerns including poor working conditions and exposure to toxic chemicals, bribery, and corruption (IEA, 2022b). These problems are particularly prevalent in the Democratic Republic of Congo. ESG issues are rightfully receiving ever-increasing attention. Mining projects and stakeholders face more scrutiny, leaving the full value chain from the mining company, through downstream industries, investors and governments open to regulatory, ethical, and reputational risks. Careful consideration of ESG risks must form an integral part of a sustainable energy transition and not least the sourcing of minerals needed to support it.

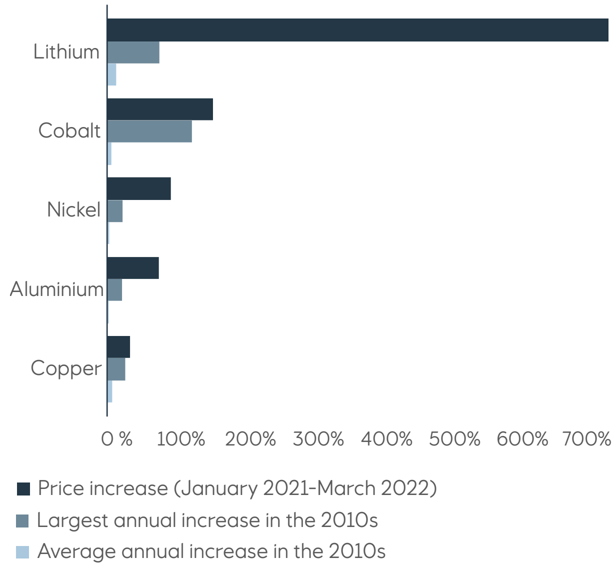
Public reports of governance related risks by region, 2017-2019



Source: IEA (2022b)

The prices of critical minerals have increased steadily over the past decades. Disrupted supply chains and concerns around tightening supply in relation to the Covid-19 pandemic and Russia's invasion of Ukraine have sent the prices of many critical minerals soaring to unprecedented highs since 2020. Prices fell as China started to reopen, but the return to pre-pandemic production levels has not been as rapid as hoped, and prices are now moving sideways and, in some cases, rising again. A water shortage in China in the late summer of 2022 affected hydropower and led local governments in the Sichuan and Chongqing provinces to enforce power cuts for industrial plants and households, which in turn caused a surge in battery-grade lithium prices (Zou & Ma, 2022; BNN Bloomberg, 2022), illustrating just how sensitive mineral prices are to supply disruption and climate change effects. Higher critical mineral prices translate into increased clean energy technology costs with, for example, the cost of wind turbine manufacturing increasing by ~10% since the summer of 2020 due to rising steel and copper prices, and EV batteries increasing more than 5% over the same period due to increased lithium, nickel and cobalt prices (IEA, 2021; IEA 2022a). The lowest cost suppliers of given mineral commodities are often linked to low environmental standards, armed groups and militia, and as the awareness of ESG issues grows, the cheapest commodities may no longer be acceptable to consumers, industrial organisations and governments, which may drive the cost of clean energy technology up further.

Scale of price increase for selected energy transition minerals and metals



Source: IEA (2022a)

Long lead times for new mining projects, with the time from discovery to production in many cases being 10-20 years, significantly impact the future availability of critical minerals (IEA, 2021). Government commitments outlining clear climate ambitions and pathways are needed to speed up permitting processes and give investors the confidence to commit to projects in the years ahead.

Recent and potential future developments

Tightening markets, ESG concerns and increased material and technology costs related to the supply of critical minerals, may lead to curtailed growth in renewables, increase the use of fossil fuels, reduce energy intensity improvements and ultimately slow down the energy transition. However, the increased focus on mineral security is helping to highlight the need for diversification of supply, innovation throughout the value chain and governance that upholds and rewards high environmental and just social standards.

Critical minerals and their role in the development of clean energy technology have been included in several recent policy initiatives: The US Inflation Reduction Act (IRA, Whitehouse, 2023) sets out commitments, and offers incentives, to increase the US domestic supply of critical minerals needed for growth in electric vehicles, batteries and renewable power infrastructure. The EU's proposal for a European Critical Raw Materials Act (European Commission, 2023) aims to identify the policy actions needed to develop strategic projects for a strengthening of EU supply chains while maintaining a level playing field. And, China's 14th Five-Year Energy Innovation Plan (2021-2025) puts a strong emphasis on energy innovation by pledging an annual increase of 7% in public R&D spending (IEA, 2022c). Governments focus on mineral security and nearshoring of mineral supply chains may also limit foreign investors (such as China) from gaining or increasing ownership in critical mineral production and refining companies (Needham, 2023). All the above should help to diversify supply chains going forward. In many cases, increased investments in mines, processing plants and infrastructure must overcome so-called NIMBY and BANANA* concerns prevalent in developed countries and areas with high population density, leading to long and resource-demanding permitting processes.

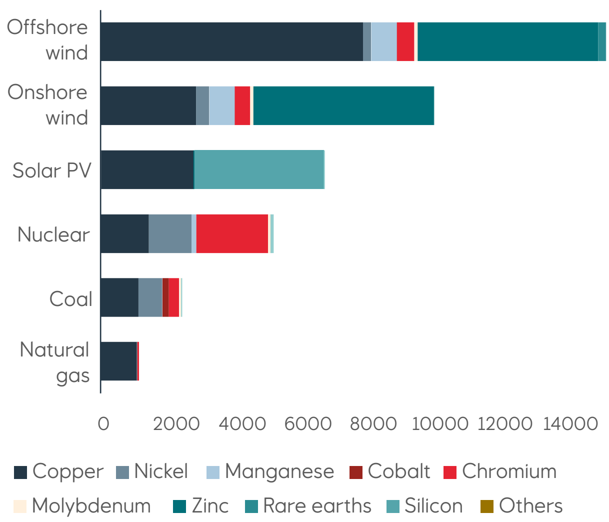
Large mineral reserves such as copper, nickel and cobalt are known to exist on the seafloor and several deep-sea mining projects have explored the possibility of extracting them (IEA, 2021). However, like on land, there are economic and environmental concerns and development has been slow. Several high-profile companies, including BMW and Samsung, have introduced a moratorium on materials from deep-sea mining until the environmental risk is better understood. Whilst deep-sea mining may play a part in increasing mineral reserves sometime in the future, this is not likely to be a solution in the near term.

Reserve use efficiency improvements through increased recycling, new and improved mining and processing methods, innovation and better technologies may all play a part in the race to secure enough minerals for the future (IEA, 2021). End-of-life recycling of minerals and metals today is closely linked to the ease of collection, price levels and market maturity, with recycling rates for precious metals such as gold, platinum and silver being very high (>50%), whilst lithium and rare earth elements are hardly recycled (<1%, IEA, 2021). Recycling is likely to significantly increase going forward and this will eventually help to ease the demand for new supply. However, even with increased recycling, it will take time before the quantities of recyclable material are substantial enough to make an impact (Serpell et al, 2021), as the minerals locked up in e.g. wind turbines built today will not be available for recycling for another 20+ years.

Whilst clean energy technologies require a larger amount of critical minerals than their fossil fuel counterparts, there are significant differences in the number of minerals needed per unit output in the various clean technologies (IEA, 2021). Solar PV requires approximately half, and nuclear about a third, of the number of minerals needed per unit output compared to offshore wind. Considering not just capacity, but the actual energy generated over the operational lifetime of each technology, these ratios change, with nuclear requiring less than a tenth of the minerals required by solar and wind technologies per unit output (World Nuclear Association, 2021). As mineral supply tightens and potentially starts to constrain the capacity expansion of technologies such as solar and wind, a more radical shift towards nuclear power than we foresee today could materialise. With small modular nuclear reactors emerging as a simpler, cheaper, more flexible and safer alternative to large-scale nuclear plants, this zero-emission energy source may regain market share and play a vital role in keeping the energy transition on track (Bocca & Wood, 2022).

Minerals used in power generation

tonnes/ MW



Source: IEA (2021)

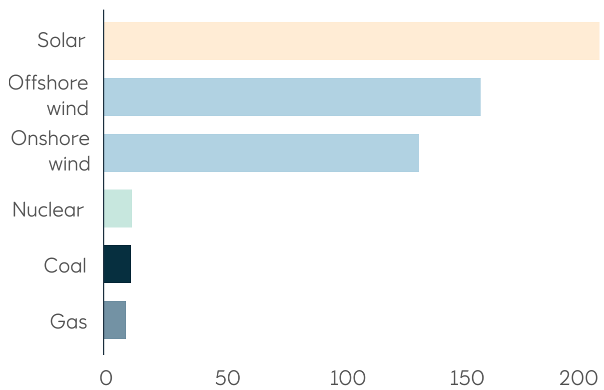
**NIMBY is an acronym for Not In My BackYard, and BANANA stands for Build Absolutely Nothing Anywhere Near Anything.*

	Plant t/MW	Indicative Capacity Factor	Generation TWh/yr	Operational lifetime (yrs)	Lifetime TWh	Plant t/TWh
Natural gas	1.2	50%	5.2	30	156	9
Coal	2.5	50%	7.5	50	375	11
Nuclear	5.3	85%	7.5	60	450	12
Onshore wind	10.1	35%	3.1	25	77.5	132
Offshore wind	15.5	45%	3.1	25	77.5	157
Solar PV	6.8	15%	2.2	25	55	207

Source: Equinor, World Nuclear Association (2021)

Critcal minerals required per unit of electricity produced

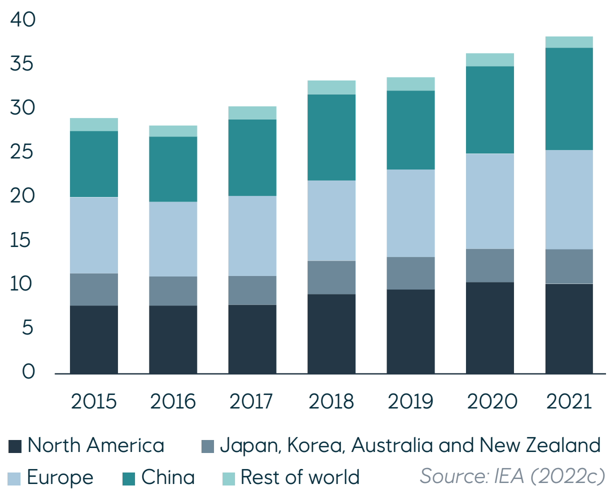
tonnes/ TWh



Source: Equinor, World Nuclear Association (2021), IEA (2021)

Innovation will perhaps be the most important enabler to secure future mineral reserves and ease demand for those in short supply or ethically compromised. Government and private sector spending on the rise and new energy technologies and improvements are materialising on many fronts as a result.

Energy R&D spending by governments



Source: IEA (2022c)

Tesla has started using lithium-iron-phosphate batteries (LFP) in their standard range vehicles (Model 3 and Model Y) for the Chinese, Asia-Pacific and European markets (Wayland, 2021; Alamalhodaei, 2021), and recently announced that they will be expanding the use of the iron-based batteries to a version of their semi electric trucks and affordable electric cars globally (Jin & Lienert, 2023). The majority of Tesla cars are currently produced using nickel-based batteries, either nickel-cobalt-manganese (NCM) or nickel-cobalt-aluminium (NCA) batteries, which contain the critical minerals nickel and cobalt. These new batteries are safer, easier to recycle and rely on raw materials that are easier to source ethically, making them a cheaper and more sustainable option than the batteries they replace. Innovation is also pushing to reduce the need for silver in solar PV panels without sacrificing efficiency. SunDrive, an Australian start-up company, is developing solar panels where copper replaces the much more expensive and resource-constrained silver paste in the panel electrode lines (Ker & Phan, 2022). In 2022 these panels were shown to have a very high efficiency of more than 25%, far superior to common industry standard roof-top mounted panels with efficiencies of around 20%. The company is currently in the process of establishing cell and module production operations and hopes to be selling panels for urban Australian rooftops by late 2023 to early 2024. Another example of innovation is direct lithium extraction from geothermal brine. This technology does not reduce the demand for lithium but helps by increasing lithium reserves and reducing the mining surface area required, thereby limiting the environmental impact of the extraction process (IEA, 2022c).

Geopolitics will continue to play a role in global energy markets both during and after the energy transition. Even if homegrown renewable energy does not end up impacting geopolitics to the same extent as oil and gas, the availability of geographically concentrated sources of key input factors will create new dependencies and room for future power games in energy. A recent example is the announced plan to nationalise Chile's lithium industry (Villegas & Scheyder, 2023). Also, dependency on international infrastructure for future transmission of electricity will create new arenas for cooperation, but also conflict.

The supply chains surrounding critical minerals are currently receiving a lot of attention from governments and industry as concerns around securing future supply rightfully intensify. This note has aimed to highlight some of the key issues related to the topic. There are, however, many other potential bottleneck issues equally, if not more imminently, critical to enabling the growth in renewable technology and the success of the energy transition. These include, but are not limited to, capital and energy requirements, human behaviour and land availability.

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