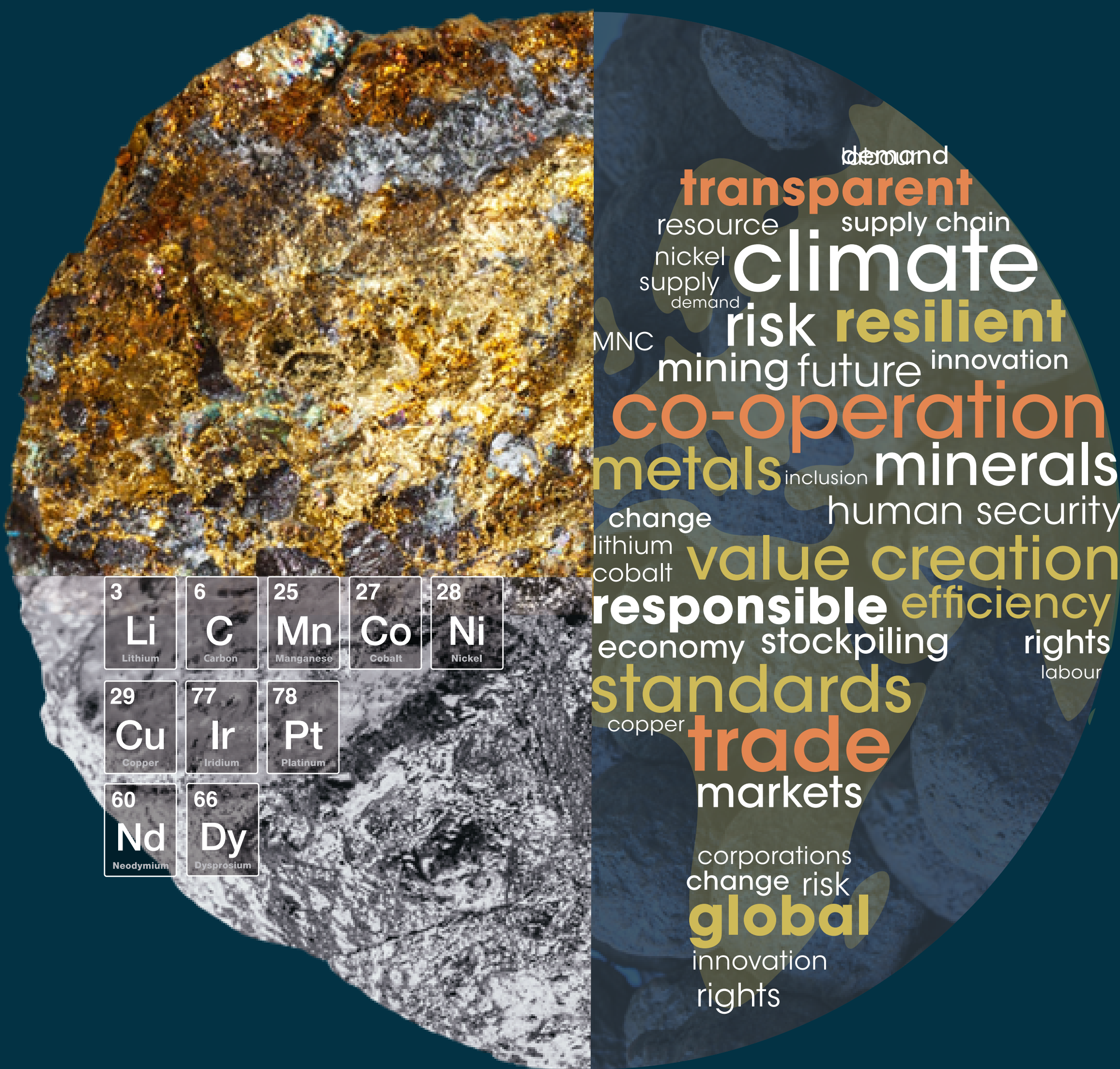
IRENA
International Renewable Energy Agency

GEOPOLITICS OF THE ENERGY TRANSITION

CRITICAL MATERIALS



EXECUTIVE SUMMARY

IRENA
International Renewable Energy Agency

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The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future. It serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

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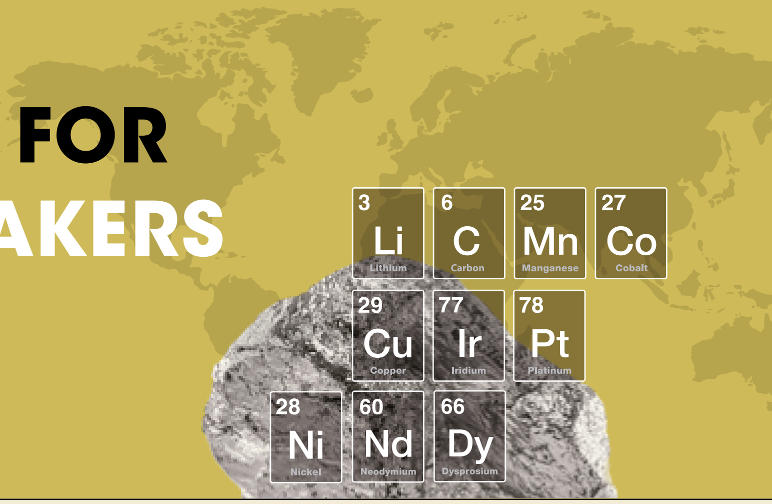
SUMMARY FOR POLICY MAKERS



The energy transition will be a main driver of demand for several critical minerals. The transition will be mineral- and metal-intensive. At present, the bulk of the demand for such materials is for uses unrelated to the energy transition; but as the transition progresses, demand for many materials is projected to grow. IRENA's 1.5°C scenario documents the vast scale of the energy transition infrastructure - and critical materials - needed to achieve climate stabilisation. This will include 33 000 GW of renewable power and the electrification of 90% of road transport in 2050. Already, a mismatch between supply and demand for several minerals is evident, with particularly high levels observed for lithium.

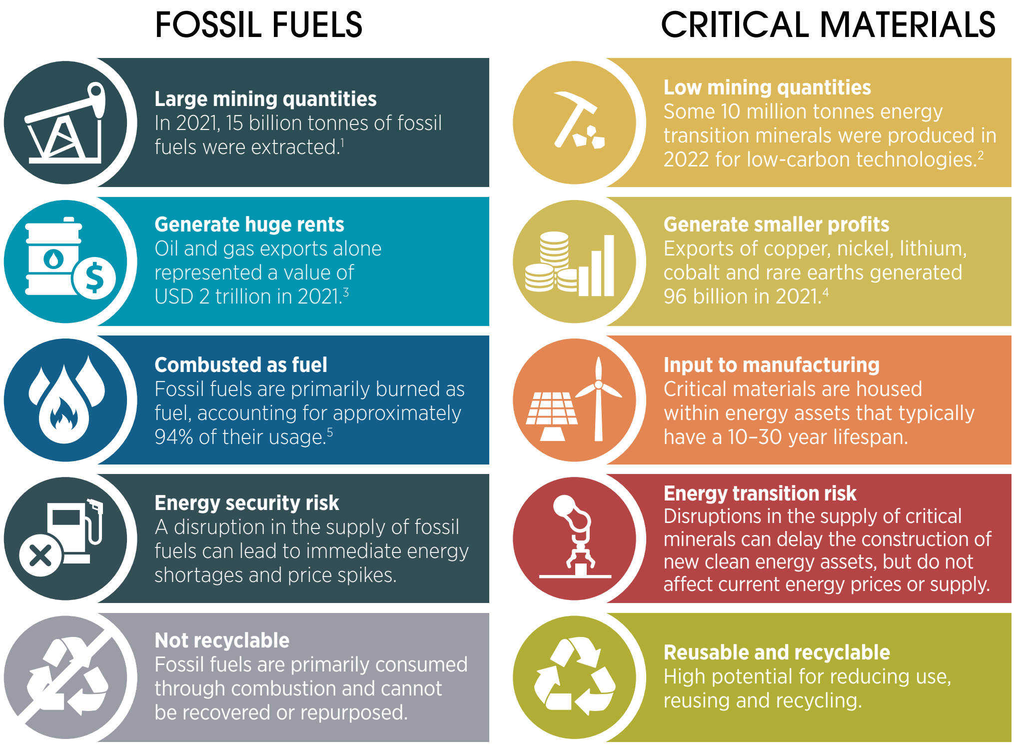
Assessment of the criticality of materials is dynamic and continuously changing owing to economic, geopolitical and technological factors. Presently there is no universally accepted definition of critical materials. Many countries and regions maintain lists of critical materials, which typically mirror current technologies, the prevailing global dynamics of supply and demand, and the context in which the assessments are conducted. The factors for determining criticality therefore remain subjective and location-specific. IRENA's review of 35 lists of critical materials reveals that 51 materials used for the renewables-based energy transition appeared on at least one list.

Critical material supply disruptions have minimal impacts on energy security, but outsized impacts on the energy transition. The current notion of energy security revolves around the continuous accessibility of energy sources, primarily rooted in concerns over fossil fuel supply. By contrast, renewable energy technologies that are already built could continue to operate for decades, even if supplies of critical material inputs were disrupted. Therefore, the risk associated with disruptions in the supply of critical materials is less about energy security and more about the potential slowdown of energy transitions.

Dependency risks and supply dynamics of critical materials fundamentally differ from those of fossil fuels, given vastly different characteristics and patterns. A prominent concern is that energy transitions will entail trading dependency on fossil fuels for dependency on critical materials. However, significant differences in their production, trade and use do not warrant such an assumption (Figure S1). Moreover, projections of critical material demand and use are fraught with uncertainties across distant time horizons, so a careful assessment of associated risks is required to understand and proactively manage them.

There is no scarcity of reserves for energy transition minerals, but capabilities for mining and refining them are limited. In the short to medium term, market constraints are likely to emerge, partly due to under-investment in upstream activities. It is unlikely that a worldwide shortfall of any one mineral will hinder the

FIGURE S1 Critical materials are fundamentally different to fossil fuels



Notes: [1] Figure is for 2021 and taken from BP's Statistical Review of World Energy. Oil and coal figures were available in tonnes; gas data were converted from billion cubic metres (bcm) to billion tonnes using the formula (1 m3 = 0.712 kg), based on BP's methodology, which is also used by Hannah Ritchie: https://hannahritchie.substack.com/p/mining-low-carbon-vs-fossil [2] Based on IRENA calculations, production of materials (copper, lithium graphite, nickel, cobalt, manganese, rare earth elements and platinum group metals) for renewable energy-related technologies in 2022 amounted to some 10 million tonnes (megatonnes) (see Chapter 2 for more details). [3] in 2021, exports of crude petroleum (HS 2709) generated USD 951 billion; refined petroleum (HS 2710) generated USD 746 billion; liquefied natural gas (HS 27111100) generated USD 162 billion; and natural gas in gaseous state (HS 271121) generated USD 173 billion. [4] In 2021, exports of copper ores and concentrates (HS 2603) generated USD 91.1 billion; nickel ores and concentrates (HS 2604) generated USD 4.24 billion; cobalt ores and concentrates (HS 2605) generated USD 118 million. With respect to rare-earth metals, scandium and yttrium (HS 280530) generated USD 586 million. [5] Calculated from IEA's World Energy Balance (2020), available from: www.iea.org/Sankey.

energy transition. Production has surged for many energy transition minerals, and reserves mined from economically viable sources have grown. Moreover, disruptive innovation - such as efficiency improvements and material substitutions - are already reshaping demand.

The mining and processing landscape of critical materials is geographically concentrated, with a select group of countries playing a dominant role. In the mining of critical materials, dominant positions are held by Australia (lithium), Chile (copper and lithium), China (graphite, rare earths), the Democratic Republic of Congo (cobalt), Indonesia (nickel) and South Africa (platinum, iridium). This concentration becomes even more pronounced in the processing stage, with China currently accounting for 100% of the refined supply of natural graphite and dysprosium (a rare earth element), 70% of cobalt, and almost 60% of lithium and manganese (Figure S2).

FIGURE S2 Key mining countries for select minerals

Cobalt (27 Co)	
Democratic Republic of the Congo	70.0%
Indonesia	5.4%
Russian Federation	4.8%
Australia	3.2%
Canada	2.1%
Cuba	2.0%
Philippines	2.0%
Others	10.5%

Copper (29 Cu)	
Chile	23.6%
Peru	10.0%
Democratic Republic of the Congo	10.0%
China	8.6%
United States	5.9%
Russian Federation	4.5%
Indonesia	4.1%
Australia	3.7%
Zambia	3.5%
Mexico	3.3%
Kazakhstan	2.6%
Canada	2.4%
Poland	1.7%
Others	16.1%

Dysprosium (66 Dy)	
China	48.7%
Myanmar	23.1%
Australia	7.6%
United States	2.9%
Canada	2.7%
Others	15.0%

Graphite (6 C)	
China	64.6%
Mozambique	12.9%
Madagascar	8.4%
Brazil	6.6%
Others	7.5%

Iridium (77 Ir)	
South Africa	88.9%
Zimbabwe	8.1%
Russian Federation	2.9%
Others	0.1%

Lithium (3 Li)	
Australia	46.9%
Chile	30.0%
China	14.6%
Argentina	4.7%
Brazil	1.6%
Others	2.2%

Manganese (25 Mn)	
South Africa	35.8%
Gabon	22.9%
Australia	16.4%
China	4.9%
Ghana	4.7%
India	2.4%
Brazil	2.0%
Ukraine	2.0%
Côte d'Ivoire	1.8%
Malaysia	1.8%
Others	5.3%

Neodymium (60 Nd)	
China	45.8%
Australia	23.1%
Greenland*	8.2%
Myanmar	7.4%
Brazil	4.4%
India	2.1%
Others	9.0%

*Kingdom of Denmark

Nickel (28 Ni)	
Indonesia	48.8%
Philippines	10.1%
Russian Federation	6.7%
France (New Caledonia)	5.8%
Australia	4.9%
Canada	4.0%
China	3.3%
Brazil	2.5%
Others	13.9%

Platinum (78 Pt)	
South Africa	73.6%
Russian Federation	10.5%
Zimbabwe	7.8%
Canada	3.1%
United States	1.7%
Others	3.3%

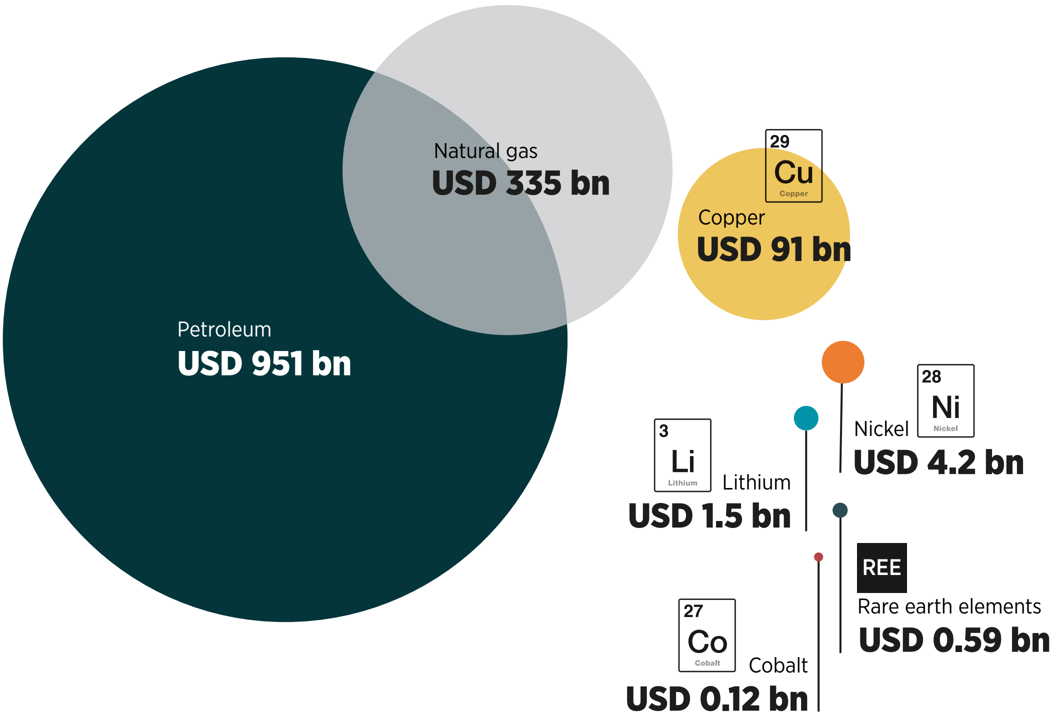
* latest data available as of 2023

Source: (US Geological Survey and US Department of the Interior, 2023; JRC, 2020; USGS, 2023b).

The mining industry is dominated by a few major companies, yielding small and often oligopolistic markets. These large multinational corporations and state-owned or -controlled enterprises operate across multiple countries and possess the resources and skills needed to develop complex mines. As a result, the industry is highly concentrated, with a few companies controlling a significant portion of global production and trade. The top five mining companies control 61% of lithium output and 56% of cobalt output.

Trade in critical materials is many orders of magnitude smaller by value than trade in fossil fuels. Unlike oil, most critical materials are not widely traded on exchanges. While this limits opportunities to hedge against price volatility, it allows commodity traders to play a key role in matching producers and consumers.

FIGURE S3 Value of exports for selected commodities (2021)



Source: (UN COMTRADE database).
Note: Numbers represent trade in raw, unprocessed fuels and ores only.

The full extent of reliance and exposure to disruptions is not always obvious. Mineral commodities sourced from different countries can be embedded in imported finished and semi-finished products, thus obscuring potential links and vulnerabilities. Moreover, import transactions are sometimes attributed only to the country of the last shipment, not to the country in which the material was originally mined or manufactured.

Each critical material has a unique geography of trade which, on an aggregate level, entangles countries in a broader web of interdependence. All countries rely on a functioning global market for critical materials and related technologies, given that they either import these commodities or rely on a steady demand for their materials, components or finished products. Trade patterns vary enormously across countries, sectors and technologies, and reveal the true interdependence of countries in terms of mineral supply and demand.

Supply chains are currently vulnerable to diverse geopolitical risks (Figure S4). Interruptions in the supply of minerals can affect multiple industries and reverberate throughout the economy. Supply shortages and related risks could arise, particularly in the short to medium term, as demand for selected materials increases, and mining and processes remain concentrated. In the medium to long term, trade flows for critical materials are unlikely to lend themselves as easily to geopolitical influence as oil and gas. This is because reserves of such materials are abundant, geographically widespread and can be processed in many locations.

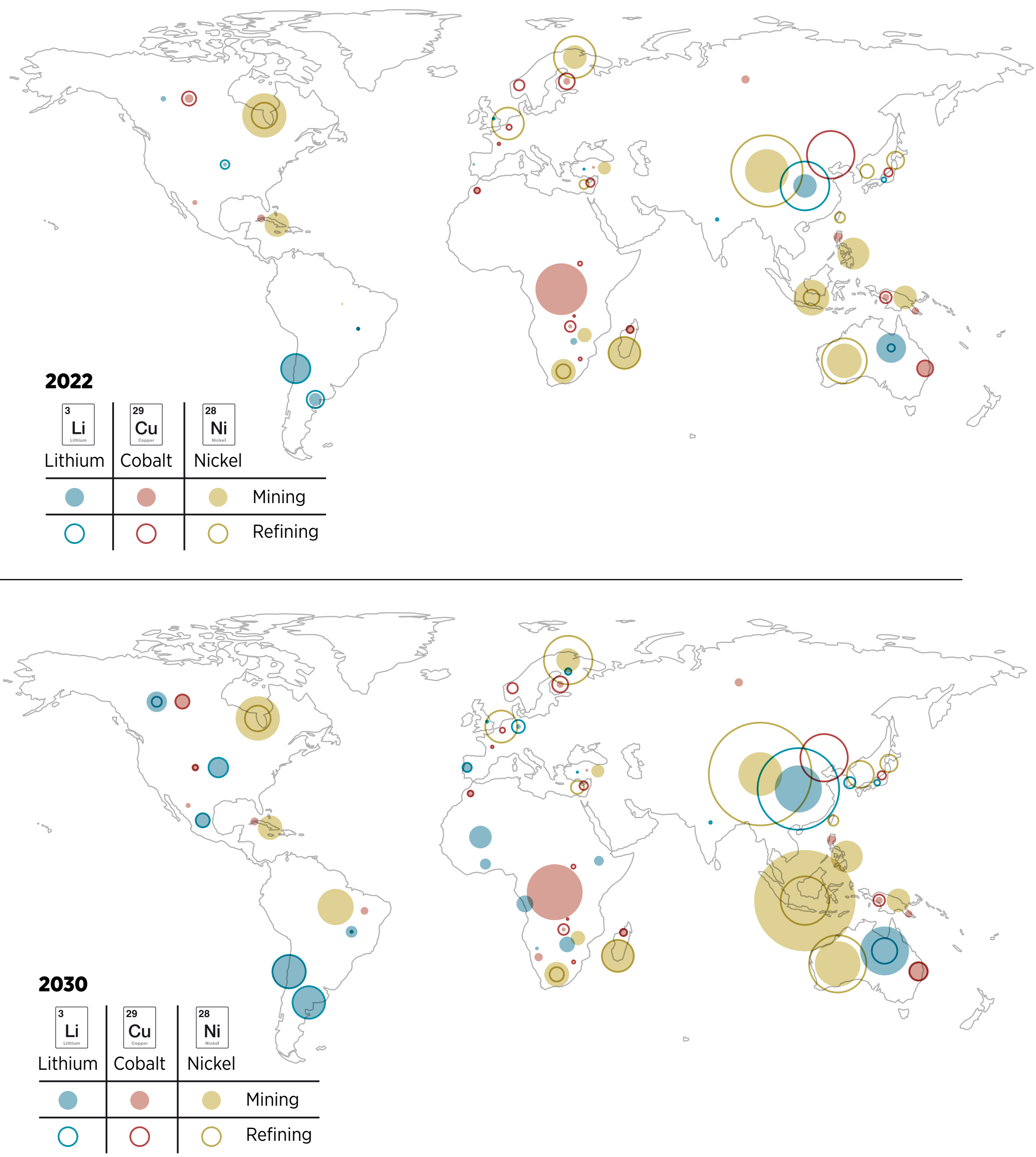
FIGURE S4 Key geopolitical risks to the supply of materials

Critical materials trade flows are not likely to be cartelised. Mineral supply is concentrated geographically, and corporations with large market shares in key segments of mineral value chains dominate their mining and refinement. This concentration of production could potentially lead to the formation of commodity cartels. However, previous attempts to establish such cartels have mostly failed, serving as a significant deterrent for many producer countries.

Geopolitical considerations should consider structural trends that could have long-term implications for the availability of, and demand for, mineral commodities. These trends include not only the geographical concentration of mining and processing but also the decline in mineral ore grades, the substitution possibilities for certain materials, and end-of-life management, among others. These factors have the potential to magnify the impact - and in some instances the probability - of geopolitical risks.

The centralised supply chains for many materials are likely to remain as they are for the foreseeable future. Many countries are trying to restructure supply chains, but new mining and processing facilities have long lead times, making it difficult to rebalance supply and demand dynamics (Figure S5). Moreover, adjusting these supply chains necessitates careful balancing of economic factors, environmental impacts and the well-being of local populations.

FIGURE S5 Mining and refining supply for selected critical materials, 2022 and 2030



Source: (BloombergNEF, 2023).

Disclaimer: These maps are provided for illustration purposes only. Boundaries and names shown on the maps do not imply any endorsement or acceptance by IRENA.

Innovations in technology can influence demand by introducing substitutes, enhancing efficiency, optimising designs and incorporating new materials. Disruptive innovation is adding to the uncertainty of future demand. For example, changes in electric vehicle battery chemistry over the past eight years have significantly reshaped the demand for specific materials. As new technologies continue to emerge, the market is likely to experience further shifts before eventually consolidating around a limited number of dominant materials and technologies. Consequently, predicting future demand for certain materials can be quite difficult, particularly in the long term.

Stockpiling of energy transition technologies is not a robust solution for mitigating supply risks. Critical materials are indispensable for manufacturing and constructing energy assets. This brings into question the efficacy of stockpiling transition minerals for the energy sector compared to other sectors, such as defence. If not handled judiciously, stockpiling can exacerbate market limitations, drive up prices, and lead to an uneven energy transition that excludes poorer countries and delays climate action.

Critical material reserves are widely distributed, opening opportunities to diversify the mining and processing of materials. Developing countries currently account for much of the global production of the materials needed for the energy transition, and their share in reserves is even greater, but not fully explored (Figure S6). For example, Bolivia has 21 million tonnes of lithium reserves - more than any other country - but it produced less than 1% of world supply in 2021. Countries can utilise their mineral resources to draw in industries involved in the middle stages of production (processing) or even in the end stages (battery and electric vehicle manufacturing).

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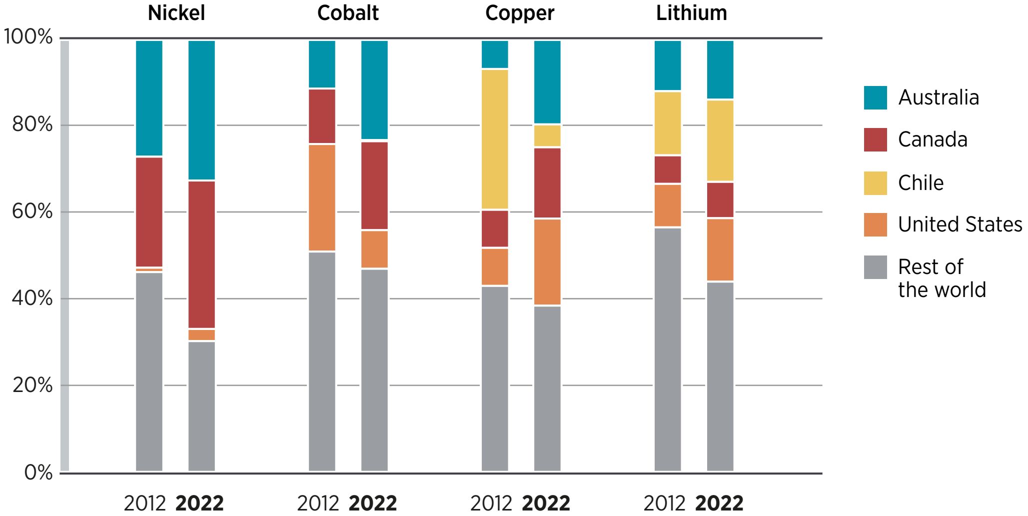
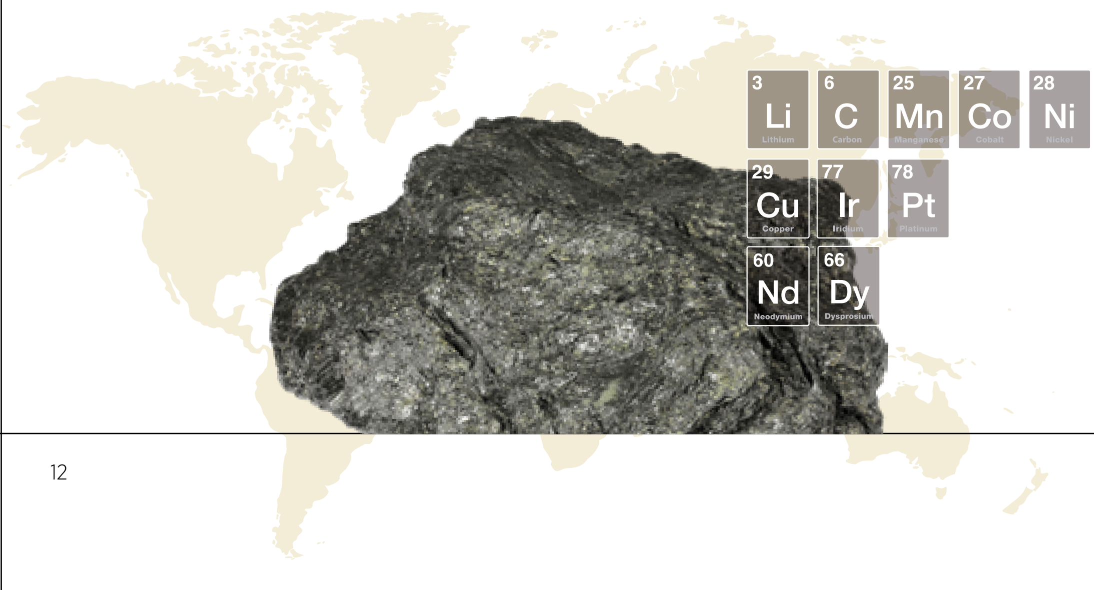
FIGURE S6 Share of global exploration budget for materials by country, 2012 and 2022



Key new players in 2022	Nickel	Cobalt	Copper	Lithium
	Gabon	Bosnia and Herzegovina	Afghanistan	Côte d'Ivoire
	Peru	Chile	Cuba	India
	Poland	Greenland*	Cyprus	Morocco
	Solomon Islands	Spain	Eritrea	Sweden
	Tanzania	Tanzania	Tanzania	United Kingdom
	28 Ni Nickel	27 Co Cobalt	29 Cu Copper	3 Li Lithium

* Kingdom of Denmark

Based on: (S&P, 2023).



An estimated 54% of energy transition minerals are located on or near indigenous peoples' land, underscoring the need for robust and early community engagement. Over 80% of lithium projects and more than half of nickel, copper and zinc projects are located in the territories of indigenous peoples. More than a third of mineral projects relevant to the energy transition are on, or near, indigenous territory or farmers' land that faces a combination of water risk, conflict and food insecurity. Over 90% of platinum reserves and resources, for example, are on, or near, indigenous peoples' or rural land facing these three risks, followed by molybdenum (76%) and graphite (74%).

The pursuit of critical materials could spark geopolitical competition in areas known to contain significant deposits, such as the Arctic, outer space and the deep sea. The Arctic is known to have vast reserves of critical materials such as nickel, zinc and rare earths, and the region's mineral abundance contributes to its strategic importance. Given the presence of ample terrestrial reserves, a cautious approach is warranted in the case of outer space and the deep sea, due to uncertainties surrounding potential environmental impacts and regulatory frameworks.

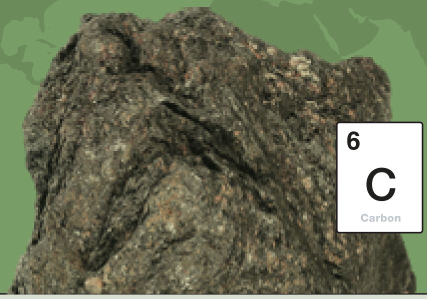
Helping developing countries to realise new opportunities in supply chains could improve resilience while narrowing the global decarbonisation divide. A key question is whether the energy transition supports developing countries to not just increase their exports of primary ores but to also move up the value chain and attract higher-margin activities such as mineral processing. Processed materials like steel and alumina do not just command significant price premia over unrefined ores; they also reduce the input cost of infrastructural and industrial projects, spurring local economic development.

Regional co-operation could help countries capture a greater share of the value of producing minerals. Rather than pursuing one-on-one deals with - often - foreign companies, co-ordinated regional approaches could be more effective in ensuring that conditions attached to foreign investment are favourable for mineral-rich countries. Co-ordination across regions is also important, as most countries would benefit from pooling respective mineral supplies if they intend to build downstream industries.

The patchwork of international and transnational initiatives requires greater coherence to bring about more responsible, sustainable and transparent supply chains. The growing recognition of challenges associated with the critical materials supply chain has spurred the development of an array of initiatives and regulatory frameworks by governments, businesses and civil society groups. Most of these are voluntary. The result is a patchwork of standards that risks sowing confusion for stakeholders and highlights the need for greater visibility and coherence.

A renewables-based energy transition, if well-planned and executed, can rewrite the legacy of extractive industries. As has been the case with extractive industries for centuries - and even with today's awareness and standards - mining activities and processes carry risks for local communities such as labour and other human rights abuses, land degradation, water resource depletion and contamination, and air pollution. Stronger international co-operation to raise and enforce standards and longer-term corporate views will be essential for sustainable development and social license.

POLICY CONSIDERATIONS AND THE WAY FORWARD



IRENA's Global Commission on the Geopolitics of Energy Transformation noted in its 2019 report that bottlenecks in critical materials were on the radar of policy makers (GCGET, 2019). Critical materials were already perceived to be scarce - in part because, like all commodity markets, these markets are cyclical. When demand rises, supply takes time to respond, particularly as new mining projects have long lead times. The Commission noted the geological abundance and wide distribution of material reserves, recognising that they are often expensive and polluting to mine and produce.

This report echoes the initial observations from the Commission. With the pressure to accelerate the energy transition in line with the 1.5°C pathway, a vast deployment of energy transition technologies is required by 2030. IRENA's *World Energy Transitions Outlook* (WETO) estimates that an average of 1 000 GW of renewables will need to be deployed annually. WETO also emphasises that enabling infrastructure will be essential to accommodate high shares of solar and wind, cross border electricity trade, electrification of end uses such as transport, and green hydrogen production and trade. Combined, these technologies are dramatically increasing demand for critical materials.

It is widely recognised that the supply chains for many critical materials are concentrated in a few countries and in the hands of a limited number of companies. This concentration creates vulnerabilities and uncertainties for both consuming and producing countries that could affect the deployment, cost and sustainability of energy transition technologies. However, security of supply is only part of the story. IRENA has consistently urged a holistic approach to all aspects of the energy transition to proactively shape outcomes and manage risks. This is particularly important in the pursuit of critical materials, given a legacy of poor labour standards, displacements, polluted waterways and degraded land in the communities in which mines operate. Moreover, the growing demand for critical materials opens new opportunities for developing countries rich in resources - especially to capture greater economic value. Additional economic, social, environmental and geopolitical implications may also emerge as critical material markets expand. It is therefore essential that the diversification of critical materials supply chains is achieved both quickly and prudently. Some of the key considerations for policy makers are outlined below.

Comprehensive, economy-wide evaluations of critical material demand are essential to identify potential risks and help avoid competition between sectors.
Countries should carefully assess the effects of surging demand for critical materials across all economic sectors, in line with their net-zero strategies. Currently, most demand for these materials comes from sectors unrelated to the energy transition, including electronics, aviation, defence, healthcare, and steel and aluminium production. However, the demand landscape is quickly evolving with the rollout of renewable energy technologies, batteries and electric vehicles. Furthermore, the modernisation and expansion of grids are contributing to the increase in material use. In the short to medium term, it will be important to maintain visibility on how the growing demand for materials in energy will impact overall demand in order to assess possible trade-offs and strategies, and avoid competition between sectors and industries.

No country alone can fulfil its demand for all critical materials, so collaborative strategies that benefit all involved need to be developed and implemented.
Given the extensive lead times for establishing new mines and processing plants, concentrated supply chains are expected to persist in the near future. Countries should aim to develop dual strategies to ensure co-operation to keep markets functioning while also working to diversify supply chains in the long term. Many bilateral, regional and industry-led initiatives focus on supply chain challenges, which could be leveraged for co-ordinated policy action. At the global level, IRENA's Collaborative Framework for Critical Materials is an established platform to exchange knowledge and best practices, and co-ordinate actions to ensure that minerals and materials continue to sustain an accelerated energy transition.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Comprehensive assessments of critical materials should be conducted for each mineral to fully grasp the dependencies, risks and innovations that may affect supply and demand.
Despite the long list of identified critical materials, not all are equally important for the energy transition, nor are their criticality assessments consistent. For instance, innovation has resulted in an increased use of substitute materials for those considered critical, such as neodymium, copper, and lithium. Policy makers should continue to foster innovation to decrease dependency on particular materials and tackle specific challenges associated with each one. along the entire supply and demand chains. Regular revisions and evaluations of critical material lists are also necessary due to the rapid innovations occurring in production.

Geopolitical risks can be mitigated through enhanced investment in research and development, which would expedite the creation of alternative solutions, boost efficiency, and expand recycling and repurposing options.
Several strategies can be employed to prevent major supply challenges leading up to 2050, with a focus on this decade. Key among these are product design strategies to minimise the use of critical materials, and the recycling and reuse of products to reclaim scarce materials. Recent trends are promising, such as battery manufacturers minimising their reliance on critical material supplies. Policy makers should support innovations that lower demand and foster a circular economy to ensure long-term material security.

Greater data transparency and oversight of certain critical materials are required to mitigate uncertainty in supply and demand projections.
The starting point should be the collection of more detailed information and data on reserves, production, investment, and pricing, among other factors, to track current supply and increase market transparency. The adoption of international quality standards and certification for key products involving critical materials could also facilitate market formation. This effort should be accompanied by the development and regular updating of demand scenarios, providing greater visibility into potential gaps and the impacts of innovation. Any short-term policy actions, such as stockpiling, should be carefully assessed to avoid unintended impacts on climate action.

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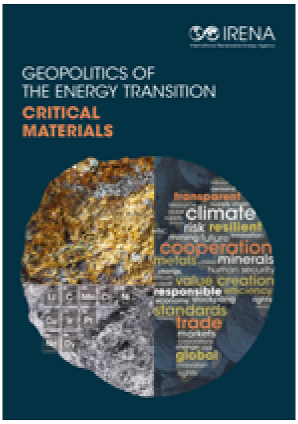
Developing countries can tap into their mineral resources and retain more economic value, forming the cornerstone of a diversification strategy that also contributes to global equity and stability.
In addition to policy that can ensure domestic value added and promote green industrialisation, diversification of supply chains must include a strategy for trade and cooperation between developed and developing countries. A balanced and co-operative approach in foreign policy engagement requires the importing states to support industrial development in developing countries beyond extractive patterns in critical material supply chains. This entails fostering partnerships, including with the private sector, advocating responsible sourcing practices, supporting capacity building in producing countries, promoting transparency and accountability, and investing in sustainable initiatives. These concrete steps can help importing states contribute to equitable and sustainable development, ensuring a more inclusive and mutually beneficial approach to procuring critical materials, while securing the long-term resilience of material supply chains.

International co-operation is crucial in creating transparent markets with coherent standards and norms, grounded in human rights, environmental stewardship and community engagement.
The energy-driven mineral boom offers a chance to rewrite the legacy of the extractive industry. Known issues surrounding mining practices need a proactive response from both nations and corporations. Importer and exporter countries must collaborate to develop supply chains that uphold clear standards regarding human rights, environmental concerns and community engagement. These standards are essential to human security and their absence is one of the root causes of geopolitical instability. In this regard, mining corporations should be held accountable for the responsible management of extraction processes. This requires engaging in inclusive dialogue encompassing the fair distribution of risks, inputs, creative contributions and resulting value. A global effort under the auspices of the United Nations could play a key role in ensuring critical material value chains are fair, equitable and transparent.



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