

Critical minerals

The investment vacuum

The global transition away from hydrocarbons as an energy source means a new ecosystem encompassing renewable power generation, storage, transmission and use needs to be built. This 'infrastructure' needs investment, but we argue that the oil industry – and the large end of the minerals extraction industry – has been slow to embrace newer, smaller and high-growth commodities and this vacuum means slow supply growth and, inevitably, high commodity prices. Governments are beginning to identify the risk that there are not enough well-funded, permitted, high-quality companies in most capital markets focused on critical minerals.

The demand pull: More than EVs

This report is another in our series on two of our major global themes, namely **energy transition** and **critical minerals**. The demand is not just about electric vehicles (EVs). Renewable energy generation needs minerals such as rare earths for wind turbines, and graphite, lithium and nickel for battery energy storage systems for power grids, and silver for solar panels. Charging infrastructure will need large amounts of copper. The impact on energy systems will accelerate demand growth rates to over 20% for several years for some of these metals, with industries needing to be 4–5x as large by the end of the 2020s – an unprecedented demand shock. In this note we discuss why certain materials are critical, how their demand is affected by energy transition, how current and future supply could evolve and who the major listed producers are.

And the policy push: Decarbonising and security

Governments are rightly wary about swapping one set of geopolitical risks for another as energy systems change. Ambitious plans to decarbonise transport and industry through policies such as net zero by 2050 and mandated end of internal combustion engines need to be balanced with making sure the materials and supply chains can cope and new risks are not created. This catch up in critical materials policy is underway, with the past 12 months seeing explicit critical minerals policies being launched in the United States, Europe, the UK and Canada. Some key end users are beginning to identify long-run supply risk and backward integrate (eg General Motors, most notably in lithium and rare earth magnets). We argue that the missing link is the lack of fresh capital, with incumbent large energy and mining firms tied to capital returns rather than long-term growth investing.

Investors

We filter and list 78 companies in many jurisdictions that we believe are highly exposed to the structural acceleration in demand growth. The global distribution is uneven (c 48% ASX listed, c 40% North America) and is notably light in the UK/Europe (just 12%). Markets experiencing demand shocks are not for the faint-hearted. Prices for many of these commodities (nickel, lithium, rare earths) have already experienced peaks higher than 4–5x their recent lows. Investors need to consider timing and stock selection carefully, but early-stage companies with quality assets in safe jurisdictions should be prioritised in our view.

Edison themes



28 March 2023

Edison themes

As one of the largest issuer-sponsored research firms, we are known for our bottom-up work on individual stocks. However, our thinking does not stop at the company level. Through our regular dialogue with management teams and investors, we consider the broad themes related to the companies we follow. Edison themes aims to identify the big issues likely to shape company strategy and portfolios in the years ahead.

Companies mentioned in this report

Alkane Resources*
Allkem*
Anglo American
BHP
Glencore
Lepidico*
Lithium Power International*
The Metals Company*
Rio Tinto
Vale

This report also includes an appendix of over 70 companies involved in the critical mineral space listed by mineral, exchange, and major activity.

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Key conclusions

In this report:

- We estimate the current market size for critical minerals (in US\$bn) and the potential for 2030 and conclude that while some critical minerals (such as graphite, lithium and rare earths) are smaller than the dominant, large mined commodities (iron and copper), they will be of reasonable magnitude in 2030, with far higher growth prospects and more exposure to energy transition trends.
- We argue that this high growth sector is not attracting capital from either the traditional energy producers (who instead are pursuing renewables such as wind) or diversified miners (who are paying dividends and not growing).
- We summarise the regulatory and policy environment, which has developed rapidly over the past 12 months. Governments are realising that their ambitions for net zero by 2050, and the accelerated electrification of transport, could potentially create shortages and new geopolitical risks.
- We summarise the key demand drivers from a fundamental end-use perspective, current mine production and geological endowment by major producing country. Most critical minerals are not in geological short supply, though many are heavily dependent on China, either for mining or processing. Consumers and governments are realising that deglobalising these supply chains is now urgent.

Critical minerals is not a well-defined term, but typically refers to materials exposed to energy transition or defence applications, with supply chains that are not well developed or that involve geopolitical risk. In this note we discuss lithium (used in batteries), rare earths (used in permanent magnets in wind turbines and EV motors), cobalt (used in some battery chemistries), nickel (which has a growing battery impact) and graphite (used in battery anodes).

We acknowledge this is a subset of a much wider group of minerals critical to both energy transition and national security. Metals not commonly thought of as critical play important roles in decarbonisation and energy transition (ie silver due to its use in solar panels). Notable other exclusions and major issues include copper, which is critical for electrification and charging infrastructure, but has its own complex and major issues, principally related to the decline in greenfield exploration spending and the scale of capital and planning needed for the industry to expand. Similarly, fertilisers are critical for long-run demographic development and food security and have a unique set of geopolitical issues.

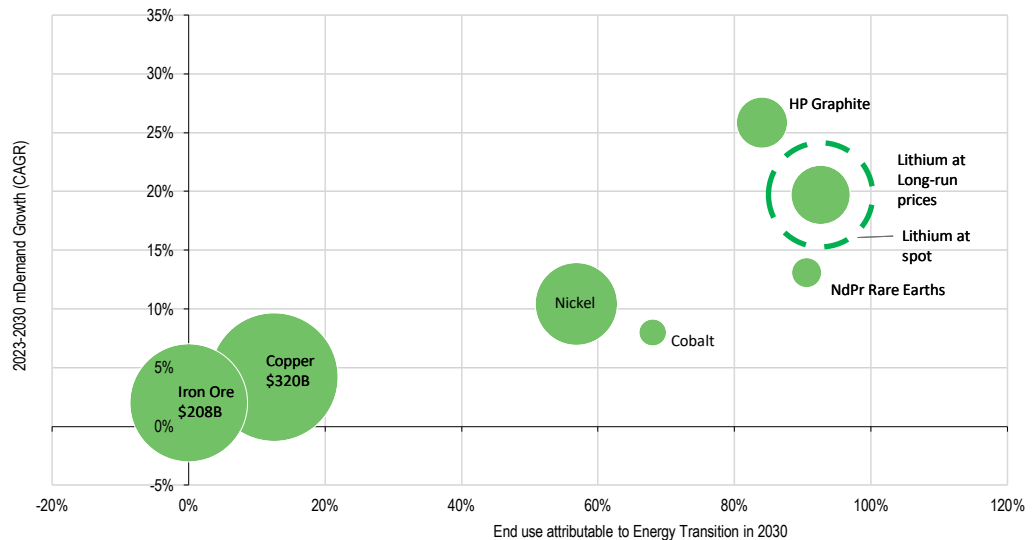
What matters most: Sizing the market

Some of the critical minerals markets are relatively small at present, which is contributing to a lack of investment. Below we show the relative market size in 2030 (in nominal terms at our long-run commodity price assumptions and 2030 levels of demand, using our projections of demand growth by metal). We also highlight the potential lithium market size at prices closer to recent peaks in spot prices (US\$70,000/t rather than our long-run assumption of US\$23,500/t) as the long-run equilibrium in lithium is particularly uncertain (see our recent note, [Lithium's adolescence](#), for a fuller discussion on the challenges of equilibrium pricing in a high-growth industry).

Most of these industries are smaller than the major mining industries such as copper (which in 2030 will be in the region of US\$320bn (c 40Mpa at c US\$8,000/t)) and iron ore (US\$270bn in 2030, US\$2.7bn at US\$100/t), but not insignificant in scale. In fact, remarkably, if the lithium market grows to 3Mt by 2030 (our estimate, and some industry estimates are now creeping higher than this), at recent spot price peaks of US\$70,000/t it would be c US\$210bn. The copper market in 2030 could

be 13x the volume of lithium but given the spot price for lithium carbonate recently peaked at 9x spot copper prices, this brings their potential 2030 market size into similar orbits.

Exhibit 1: Market size, demand growth and energy transition relevance



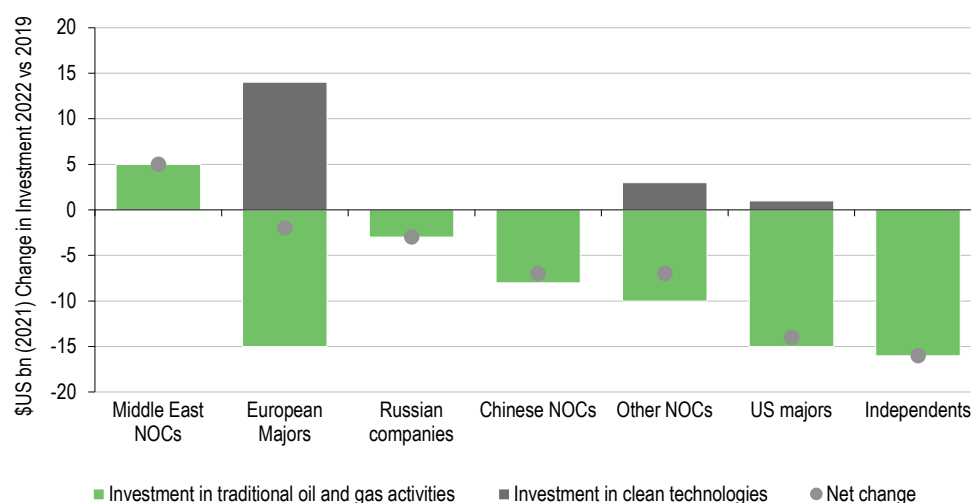
Source: Edison Investment Research

The investment vacuum

One significant challenge with the transition away from fossil fuels is the structural redirection of capital spending. Capital spending on long-dated assets in oil is falling, but this is not being redirected into energy transition materials, and the linkages between oil and mining from a corporate perspective were broken two or more decades ago.

This change in spending patterns within the oil industry can be seen in data from the International Energy Agency (IEA) shown below. The data show investment spending in traditional oil and gas assets contracted by US\$62bn between 2019 and 2022. Investment in clean technologies expanded by less than this amount (US\$18bn over the same period), but this was mostly by European oil majors and largely in offshore wind. There has been little (if any) interest by the oil industry in developing investments further upstream in mined critical minerals, and this investment will be needed build renewable energy infrastructure.

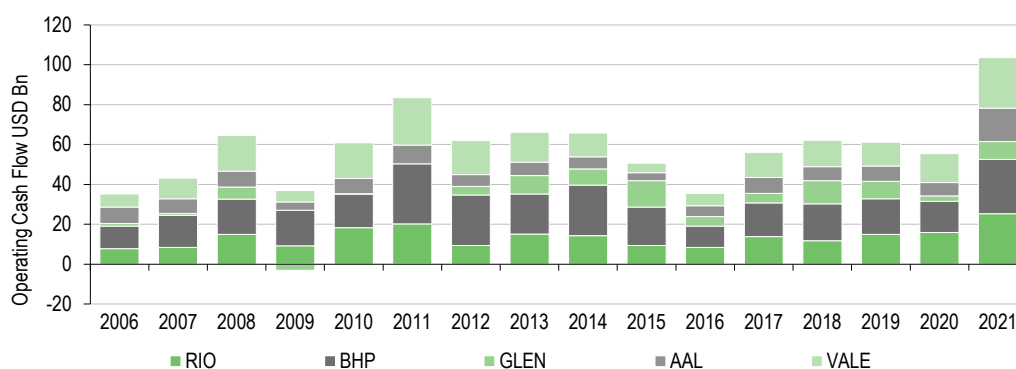
Exhibit 2: Investment spending by the oil industry is contracting (or being focused on wind) rather than being redirected to critical minerals



Source: IEA (2022), Wind Electricity, IEA, Paris <https://www.iea.org/reports/wind-electricity>, License: CC BY 4.0 and Edison Investment Research

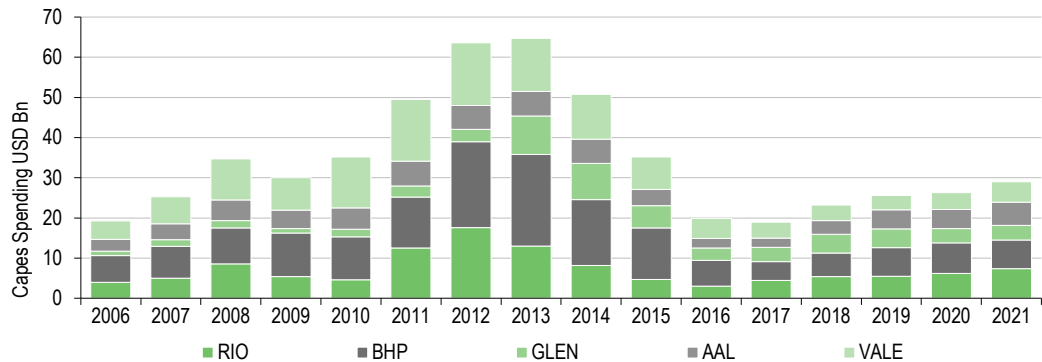
Therefore, it is up to the mining industry to fill this void. The large, global diversified miners, however, have also mostly shown little enthusiasm for pursuing the development of energy transition materials. This is not for a lack of financial resources – commodity price rises have taken the generation of operating cash flow by the global diversified majors (Rio Tinto, BHP, Vale, Anglo American and Glencore) to new records. The chart below shows operating cash flow generated by this group since 2006 – with the last fully reported year of 2021 exceeding the boom years of 2008 (early Chinese industrialisation) and 2011 (Chinese economic stimulus post the global financial crisis). Commodity prices for traditional sources of cash flow (iron ore, metallurgical coal, copper and base metals) remain high and debt levels low, so financial flexibility is considerable.

Exhibit 3: Operating cash flows of global diversified mining companies (2006–2021)

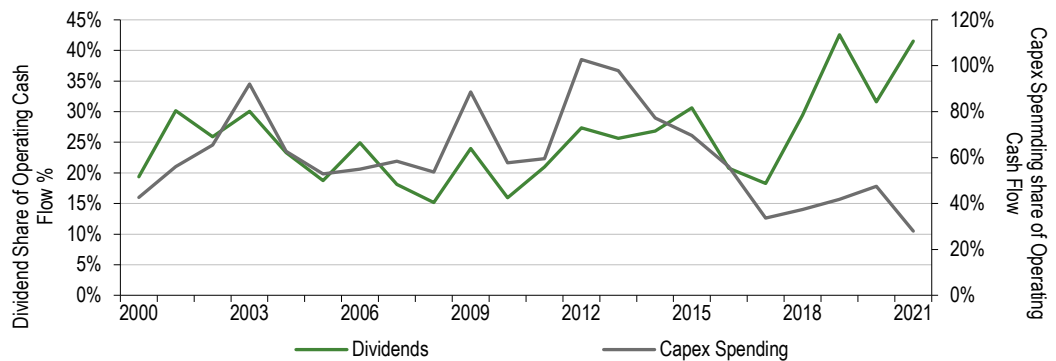


Source: Corporate reports and Edison analysis

Diversified miners can (and used to) redirect cash flow from cash generative, cyclically high commodity industries to those that are small, emerging or out of fashion. But the increasing trend has been to hold overall capital investment at low levels (as the chart below shows, total capital spending continues to increase at a gradual pace and allowing for capital inflation, companies are still achieving very little in terms of production growth). As a percentage of operating cash flow, capital spending is at the lowest level seen for this group of companies for at least the past 20 years (28% versus a longer-run average of 62%). A return to normality of cash flow allocation would, in theory, see a potential doubling (or an additional US\$30bn pa) in capital spending.

Exhibit 4: Capex of global major diversified miners 2006–2021


Source: Corporate reports and Edison analysis

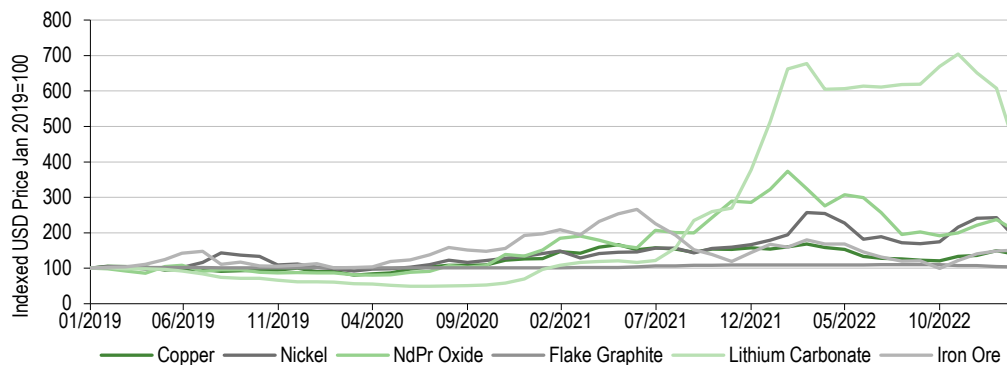
Exhibit 5: As a proportion of operating cash flow, capex is at a record low and dividends a record high


Source: Corporate reports and Edison Investment Research analysis

However, there has been surprisingly little interest from this part of the industry in taking even optional small stakes in critical minerals (Rio Tinto is a notable exception with its (still relatively small) acquisition of the Rincon Lithium project in March 2022 for US\$825m). These critical minerals industries may have been seen as too small, too different technically and without clear and obvious entry points. Large miners are also somewhat backward looking in their strategy and are still responding to the investor backlash against the capex splurge of a decade ago, favouring instead high cash returns and modest incremental growth. It is quite possible that large miners are late to the critical minerals and energy transition party – entering when the industry is larger, more profitable and too difficult to ignore.

These disconnects between oil and mining, and between large and small miners, have created a vacuum for industries like lithium, tungsten, rare earths and graphite. As a result, fresh capital or existing cash flow needs to be attracted to fund capacity growth, and the only realistic way that both of these are triggered is through higher commodity prices.

There is evidence that this trigger is already in place. The chart below shows indexed prices for a range of commodities, including key critical metals such as lithium and rare earths.

Exhibit 6: Indexed prices of various commodities 2019–present


Source: LME, industry sources, Edison Investment Research

The regulatory and policy environment

2022 was a critical year for how governments changed how they thought about commodity dependency. Some, but not all, of this change in attitude was no doubt driven by the Russian invasion of Ukraine and the realisation that energy interdependence between Europe and Russia was far more strategically and economically fragile than widely thought. There was also the realisation that the shift towards de-globalised and decarbonised energy systems immediately throws up a different set of challenges. Are there sufficient 'safe' sources of the materials needed for this transition? This question has resulted in specific policy changes in the past year.

The first major critical minerals government initiative was the passing by the **US Congress** of President Joe Biden's **Inflation Reduction Act** in August 2022, which includes commitments to increase domestic supplies of minerals critical for decarbonisation, including lithium, nickel, manganese and graphite. One example of stimulus for domestic supply is that tax credits for EVs will only apply if the materials used come from either the United States or nations with free trade agreements with the country. More recently the Pentagon has indicated that it would make hundreds of millions of dollars available to firms (including those in Canada), invoking the 1950 Defence Production Act.

The **UK** also released its first **critical minerals strategy** in 2022, with commodities such as lithium, cobalt, graphite, silicon, tin and rare earths given as examples of materials critical to decarbonisation. The aims include accelerating the UK's capabilities in supply chains and the circular economy, collaborating with international partners and championing London as a centre for responsible finance for critical minerals. There are also clear signs that regulators are trying to close the gap between environment policy and capital market regulation. For example, in 2022 the UK Financial Conduct Authority (FCA) launched an ESG advisory committee for the FCA to comply with the UK government's request for it to 'have regard' to its net zero ambitions by 2050.

In September 2022, the **European Union (EU)** announced new critical minerals legislation (**European Critical Raw Materials Act**) as part of the annual state of the union address by European Commission President Ursula von der Leyen. The act is clearly designed to protect the medium-term security of materials critical for energy transition (including lithium and rare earths) with the intention of diversifying away from dependence on China. The European Commission will be empowered to identify strategic project proposals from member states, which would benefit from streamlined procedures and better access to finance. Targets could also be set for minimum local content – examples given include a requirement that at least 30% of refined lithium demand in the EU should originate in the EU or that at least 20% of rare earth elements in waste streams are recovered by 2030. This policy builds on the EU's earlier initiative of creating the European Raw

Materials Alliance (ERMA), whose aims include the diversification of supply chains and the development of the circular economy.

This theme was returned to in a speech by President von der Leyen on 24 March, highlighting the need to accelerate the Critical Raw Materials Act and the launch of discussions with the US on a potential critical raw materials agreement. The voluntary targets announced in March include the requirement for at least 40% of processing and refining of materials to be carried out in the EU by 2030, 10% of strategic raw materials to be mined (currently 3%) and 15% to be recycled.

In December 2022, the **Canadian** government released its **Critical Minerals Strategy** with the aim to increase the supply of critical minerals and support domestic and global value chains for the 'green and digital' economy, with C\$3.8bn in federal support, including support for processing, manufacturing and recycling operations. The strategy names 31 critical minerals and defines 'critical' as having few or no substitutes; are strategic and somewhat limited commodities; are increasingly concentrated in terms of extraction and, even more, in terms of processing locations. Of this list, six are highlighted initially as having the potential to spur Canadian economic growth, and their necessity as inputs for priority supply chains. These six are lithium, nickel, cobalt, graphite, copper and zinc.

In January 2023, the **Australian** government announced a **new grants scheme** to help develop its critical minerals capability, with grants of A\$1–50m to support projects to strengthen Australia's sovereign capabilities in critical minerals. The Australian government is undertaking a wider review of its critical minerals strategy and has opened a consultation on Australia's battery strategy. The country is already a major producer of clearly critical materials such as mined lithium (spodumene) and rare earths but has yet to build integrated processing plants and relies on China and Malaysia as processing points for lithium and rare earths respectively. Australian minerals policy is mostly a function of individual states under its federal system, however given the political and global nature of critical minerals, a coordinated approach by the national government is growing. Continued government support for developing infrastructure and processing capability seems the most likely outcome to us.

Overall, the policy landscape is evolving quite rapidly. Given that the likely outcomes will include some government support but, most importantly, potentially some routes to more rapid approval processes, it seems likely that the broader mining industry will continue to promote its cause and broaden (as far as possible), the definition of what is truly critical. In our view, there is some justification for this – the mining industry has been slow to grow in recent years, and a wide variety of mineral resources will be needed for energy transition. The clear focus will be on minerals that are directly needed for energy transition and have politically challenged or underdeveloped supply chains. Below we focus on some markets that clear that bar by a wide margin.

Rare earths

Rare earths elements (REEs) are elements that are typically found together in nature and mined as a group. They are famously 'not rare' but not often found in economic concentrations. They are found in a broad range of mixes and mining operations typically convert relatively small quantities into a concentrate at the mine site, which then requires painstaking separation into individual rare earth compounds, typically oxides. China has come to dominate both mining and processing over the past 20 years.

Exhibit 7: Rare earth elements

	Rare Earth Element	Atomic Number	Atomic Symbol	Critical Application
Light	Lanthanum	57	La	
	Cerium	58	Ce	
	Praseodymium	59	Pr	High Strength Magnets
	Neodymium	60	Nd	High Strength Magnets
	Promethium	61	Pm	
Medium	Samarium	62	Sm	
	Europium	63	Eu	
	Gadolinium	64	Gd	
	Terbium	65	Tb	
	Dysprosium	66	Dy	High Strength Magnets
Heavy	Holmium	67	Ho	
	Erbium	68	Er	
	Thulium	69	Tm	
	Ytterbium	70	Yb	
	Lutetium	71	Lu	
	Yttrium	72	Ty	

Source: Edison Investment Research

Role in energy transition

Each REE has very different physical characteristics and hence very different end uses and prices. The major two elements in demand for energy transition are neodymium and praseodymium (Nd/Pr), due to their use in high-strength NdFeB magnets. Dysprosium is a smaller market, but also relevant to magnet demand growth as it improves magnet performance at high temperatures. NdFeB magnets were largely commercialised during the 1980s, initially in uses such as computer hard disk drives, but then in applications such as small electric motors. Demand has since accelerated in uses where large magnets or induced magnetic fields had traditionally dominated, principally EV motors and in large wind turbines.

Total global demand for NdPr was approximately 50,000t in 2022, with wind turbine magnets accounting for approximately 18% and EV motors accounting for approximately 15%. The balance of demand is a wide range of small electric motors used in vehicles and automation more generally.

We estimate that an EV contains c 1kg of REO (a mix of Nd oxide and Pr oxide) in the magnet, which weighs c 2.8kg. The full electrification of 100m non-commercial vehicles would require annual demand in the order of c 100,000t.

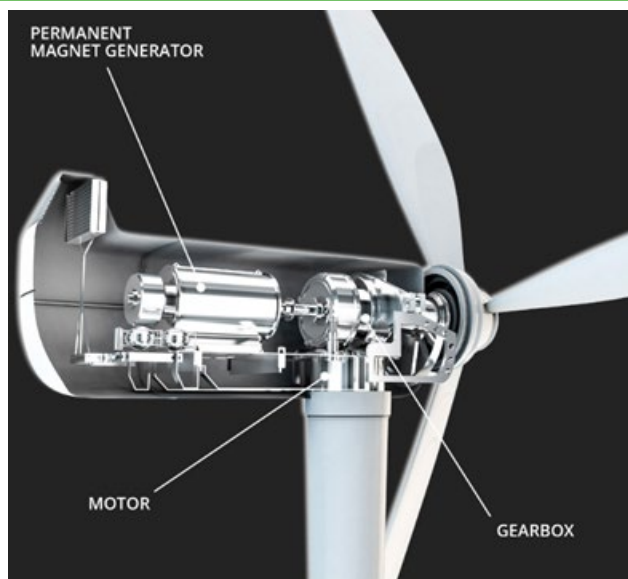
Wind energy will also strongly add to demand growth – offshore wind turbines consume approximately 213kg/MW (213t/GW) against 61kg/MW (61t/GW) for onshore turbines. Generally, there is a trend towards less complex, low speed direct drive as its operating cost improves, particularly for offshore wind farms.

According to the IEA, in 2021 wind electricity generation increased by a record 17% to 2,73TWh, resulting in total capacity of 830GW. This growth was 55% higher than that achieved in 2020 and was the highest growth among all other renewable power generation technologies. This increase was made possible due to the wind capacity additions of 113GW in 2020. However, to accomplish the IEA's Net Zero Emissions by 2050 Scenario would entail approximately 7,900TWh or 3,105.9GW of wind electricity capacity by 2030. This would need the necessary annual capacity additions for wind electricity generation to increase to almost 250GW pa, which is more than double 2020's record growth.

Roughly 22% of total wind capacity growth in 2021 was delivered by offshore wind turbines, which is the highest in history and three times the average of the past five years. At a 20% offshore/80% onshore mix, and average intensity per GW (given the intensities described above) would be 91t/GW. This implies 22.7kt of NdPr annual demand to meet this wind goal, almost 50% of current

global annual demand. To fulfil this climate goal in the wind electricity segment, annual investment in onshore wind will need to triple from US\$67bn in 2018 to US\$211bn globally in 2050 and offshore wind investments quintuple from US\$19bn in 2018 to US\$100bn by 2050 (source: IRENA).

Exhibit 8: Make up of a wind turbine



Source: Goudsmit UK

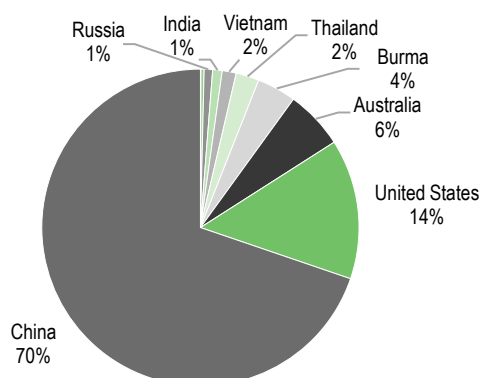
Are there alternatives?

There are alternatives, but at a cost. Both wind turbines and EVs can avoid the use of NdPr by using motors/generators that mechanically induce an electric field for their operation. However, powerful permanent magnets improve vehicle efficiency by approximately 3% for an EV, critical for adding to range and particularly useful in low-speed, high-torque stop-start city driving. A typical EV might contain 2.5–3kg of rare earth magnets, which are made using c 1kg of NdPr, with the balance being iron and boron. This means that rare earths add perhaps US\$70 to the materials cost of a vehicle at long-run prices, which is small in comparison to the trade off in other materials usage for the additional motor efficiency.

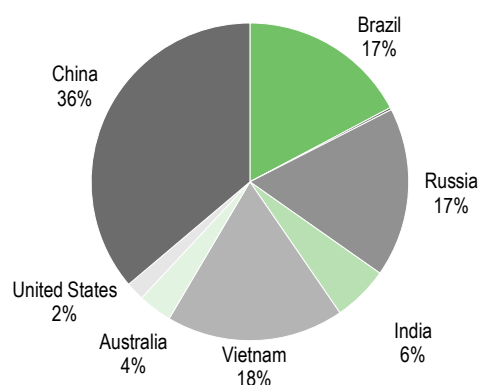
Wind turbines can also use induction motors rather than rare earth motors, but again, there are cost and efficiency issues at play. As wind power has progressively moved offshore, wind turbines have become far larger and need to be designed for minimal maintenance. This favours a direct-drive mechanism based on permanent magnets rather than highly geared, faster rotating induction motors.

How 'at risk' is supply?

Rare earths are very politically exposed. China has come to dominate rare earth mining and processing over the past two decades, partly due to lower prices forcing out western suppliers and partly because it is one industry where China has a natural resource endowment. China accounted for 70% of rare earth mined production in 2022; however, this was as high as 90% in recent years and the next largest producer (the United States, at 14%) has been sending its mined rare earth concentrates to China for processing. This is now ending, with the United States shifting to domestic rare earth separation and ultimately magnet making (its production is dominated by US-listed MP Materials, which has been striking backward integration partnerships with General Motors). Deglobalising rare earth supply chains is a long-term strategic priority in terms of supplying energy transition materials.

Exhibit 9: Global mine production – rare earths


Source: USGS and Edison Group analysis

Exhibit 10: Global reserve base – rare earths


Source: USGS and Edison Group analysis

Lithium

For a full discussion of Lithium market dynamics, please see our recent thematic report, [Lithium's adolescence](#), published in February. This report discusses the supply/demand outlook and drivers of long-run economics in lithium in detail.

Role in energy transition

Lithium-ion batteries have come to dominate battery chemistries for EVs and energy storage. Lithium is the third element on the periodic table, and the transmission of lithium ions forms the basis of the lithium based batteries for EVs.

The use of lithium-ion batteries in energy transition has in recent years experienced explosive growth, with EV batteries representing c 58% of global lithium demand in 2021, according to our estimates. With the increasing drivers of decarbonisation and ambitious climate targets, the demand for long-term EV batteries will continue to increase and we expect batteries to account for c 70% of global lithium demand by 2030. The IEA expects global EV stock across all transport modes to increase from almost 18m vehicles in 2021 to over 200m in 2030 (CAGR of over 30%) under the Stated Policies Scenario (SPS). The IEA also sees global EV stock exceeding 85m vehicles in 2025 with this number rising to 270m in 2030.

Are there alternatives?

Potentially, but lithium seems to have won the first phase of electrification and it is clear the electrification of cars will use lithium-ion technology.

How 'at risk' is supply?

Lithium is not geologically scarce, but growing an industry at scale and at the pace required for energy transition is proving a major logistical challenge. Secure supply is also a major issue. Lithium is found in brine deposits, particularly in the salt lakes of the high Andes mountains in Chile, Bolivia and Argentina, and hard rock deposits, notably in Australia. Brine deposits produce battery grade lithium carbonate and hydroxide but are relatively tightly controlled. Hard rock sources (mostly in the form of spodumene) are available, but at present are dependent on China for processing into battery grade material and chemical precursors of battery manufacturing.

It is a clear strategic priority for governments and end-users to build new alternative production routes.

Graphite

Graphite is an allotrope of carbon, rather than a metal, and comes from two main sources – mined graphite, which is processed into material suitable for battery anode manufacture and other applications, and synthetic graphite, which is produced from needle coke, a by-product of oil refining.

Mined production is in the form of flake, lump or amorphous. Mined graphite is relatively low in the value chain (lower grades of mined graphite sell for under US\$1000/t), but can be upgraded by a process of micronizing, purifying and shaping a coating, which can increase the value of the product by more than tenfold.

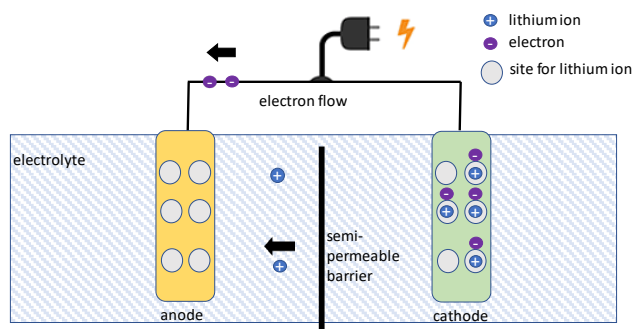
Role in energy transition

Battery manufacturing currently accounts for a relatively small proportion of total global graphite demand (approximately 8–10%), with other major end uses being graphite used as a foundry material, lubricants and in the carburization of steel. This will likely change considerably as battery end-use grows.

Graphite is critical for the functioning of lithium-ion batteries. A typical lithium-ion battery has an anode, which absorbs lithium ions as part of the charging/discharging cycle, and a cathode made from an alloy of metals. Graphite is a specific form of carbon (flat planes of hexagonally linked carbon atoms) and it is this planar structure and high conductivity that is particularly suited to its use as an anode material in the lithium ion battery.

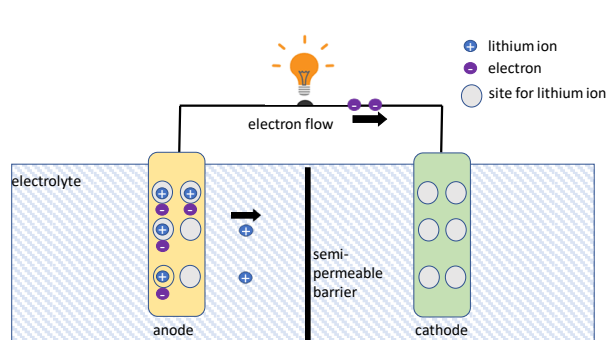
A typical EV can contain up to 70kg of graphite. Using our rule of thumb of complete EV transformation of 100m non-commercial vehicles/year, it puts the potential scope for EV demand at around 7Mt, c 7x higher than current levels. The likely outcome is more complex, as hybrid requirements are far lower and penetration rates will be more complex, though non-passenger applications (buses, energy storage) are also likely to grow considerably. This growth is highly unlikely to come from synthetic petroleum sourced graphite (as oil refining is not a structural growth industry and 7Mt would form a considerable (c 10%) part of sold carbon from oil refining). Therefore, the graphite mining industry will need to expand considerably.

Exhibit 11: Lithium-ion battery charging

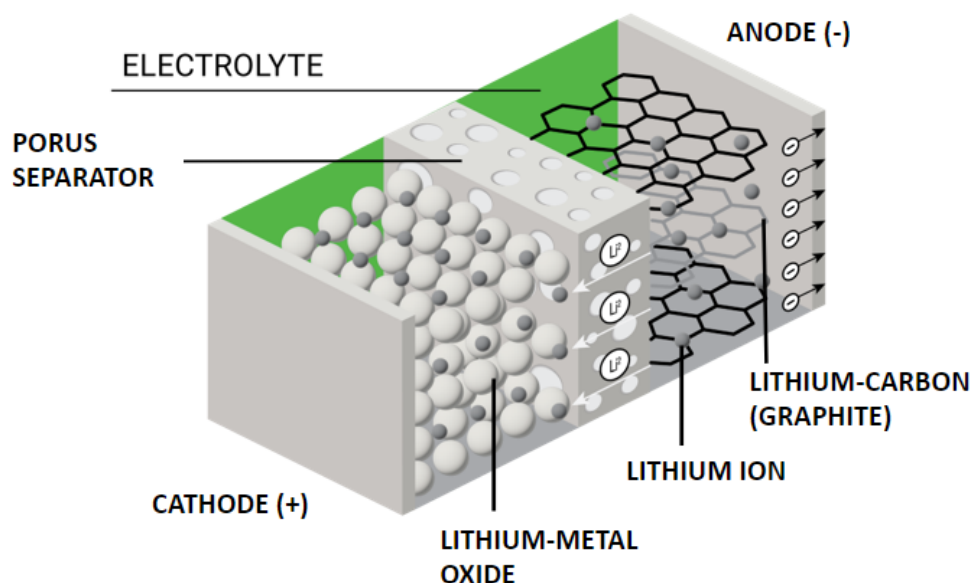


Source: Edison Investment Research

Exhibit 12: Lithium-ion battery discharging



Source: Edison Investment Research

Exhibit 13: Basic Lithium-ion battery components


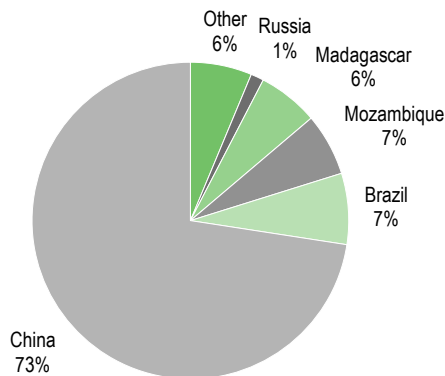
Source: TA Instrument and Edison Investment Research analysis

Are there alternatives?

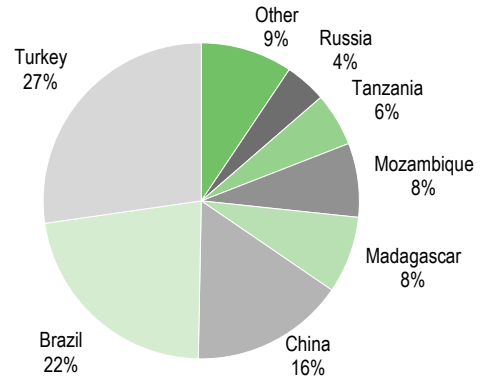
There are no alternatives yet. While there are a number of potential competing solutions including silicon use in the anode of up to 10–15%, to date this has been limited by the impact on swelling and cell degradation. More information can be found in our [Battery charge](#) and [EV outlook #2](#). Longer term, different technologies including sodium ion, solid state and lithium metal anodes are also being actively researched, although the consensus is that graphite will dominate anode technology for at least the 2020s.

How ‘at risk’ is supply?

Graphite is naturally a geologically abundant material, but there are distinct supply issues. Firstly, most battery producers prefer the consistent quality of synthetic graphite, but this section of supply will not be able to meet this high demand growth for energy transition. Needle coke is a key raw material for synthetic graphite, and its production has a strong relationship with the volume of oil refining (it is a by-product of heavier fractions of oil). Given that oil refining is not a high growth industry and, ultimately, an industry in decline in an energy transition scenario, the production of needle coke is likely to decline structurally over the longer term. Also, synthetic graphite’s other key end use is large-scale graphite electrodes for electric arc furnaces (EAFs), which are likely to grow strongly in the steelmaking industry as EAFs are less emissions intensive than traditional blast-furnace steelmaking. As a result of these two forces (declining oil refinery output and competition from graphite electrodes), synthetic graphite supply into battery material anodes is likely to be a significant structural risk over the longer term. Given that there are few other materials from the technical carbon universe (ie sold carbon products) that are suitable for the process of graphitising and refining into graphite, mined graphite is likely to be a key critical raw materials input into energy transition.

Exhibit 14: Mined graphite production is dominated by China


Source: USGS and Edison Group analysis

Exhibit 15: Graphite reserves are more widely spread than mining


Source: USGS and Edison Group analysis

Cobalt

To some extent Cobalt is a victim of its own success. High prices and political risks of supply have led to an acceleration in attempts to design cobalt-free batteries, but to date it remains a critical mineral for batteries and one that requires alternative sources.

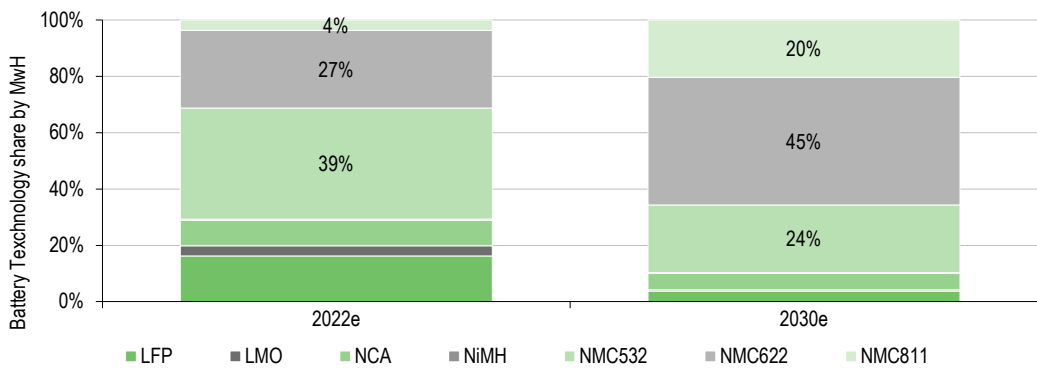
Role in energy transition

Cobalt forms part of the dominant chemistry for lithium-ion battery cathodes. Cobalt chemistry is usually shorthand by a series of codes describing the nickel, manganese and cobalt content consecutively. For example, NMC 811 is a cathode composition with 80% nickel, 10% manganese, and 10% cobalt. When lithium-ions leave a cathode, they leave with a positive charge. The remaining metals in the cathode need to change their oxidation state to maintain a neutral electrical charge and cobalt (like other transition metals) is able to do this while retaining the structure of the cathode. In NMC cathodes cobalt of at least 10% content helps the rate at which power is delivered.

Are there alternatives?

Yes and no. Cobalt is being thrifted from cathode chemistries with approximately 20% cobalt (eg NMC 532 and NMC 622) to chemistries with 10% cobalt (NMC 811), which is lowering average intensity across battery demand. There are cobalt free chemistries (eg Lithium iron phosphate, or LFP), which is in use by Chinese battery manufacturers, but there are trade-offs in performance and supply chain integration. A clear, secure source of cobalt would provide a significant boost to cobalt-chemistry batteries.

Exhibit 16: Battery technology mix

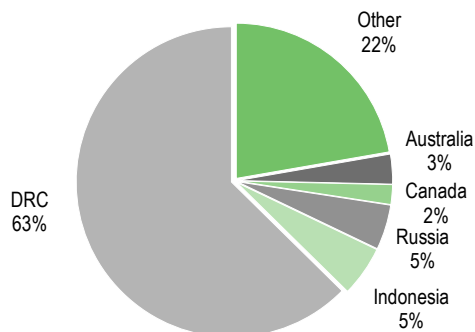


Source: Edison Investment Research. Note: LFP, lithium iron phosphate; LMO, lithium manganese oxide; NCA, nickel cobalt aluminium; NMC, nickel cobalt manganese.

How 'at risk' is supply?

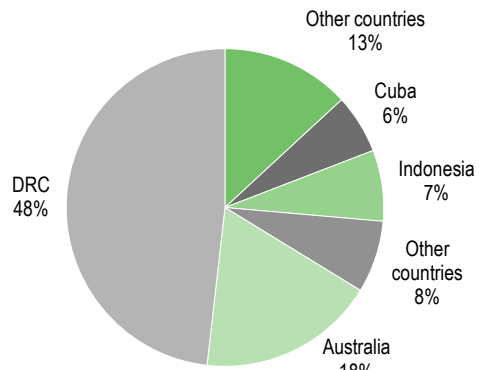
The prime risk (and driver of consumer thrifting) is the significant reliance on mine supply from the Democratic Republic of Congo (DRC). Cobalt is found as a co-product of copper mining operations and is also mined in its own right, sometimes using 'artisanal' mining methods, which can involve high rates of manual and sometimes child labour. This, in addition to general political risk of assets based in the DRC, places cobalt at considerable political and ESG risk.

Exhibit 17: Global cobalt mine production 2022



Source: USGS, Edison Investment Research

Exhibit 18: Global cobalt mine reserves 2022



Source: USGS, Edison Investment Research

Nickel

Nickel, like copper, is a major existing mining industry and its traditional end use, stainless steel, still dominates demand accounting for approximately two-thirds of global demand. Nickel use in batteries stood at 11% of demand in 2021 (according to the Nickel Institute).

Role in energy transition

As outlined above, Nickel forms the basis for most cathodes for EVs. In broad terms, an average EV battery contains 30kg of nickel, so at (again, our broad-brush order of magnetite basis) 100m non-commercial vehicles a year, this would need 3Mt nickel, roughly equivalent to doubling current global mine production. As with cobalt and other battery metals, recycling would also provide a supplementary source of supply, although at a considerable time lag.

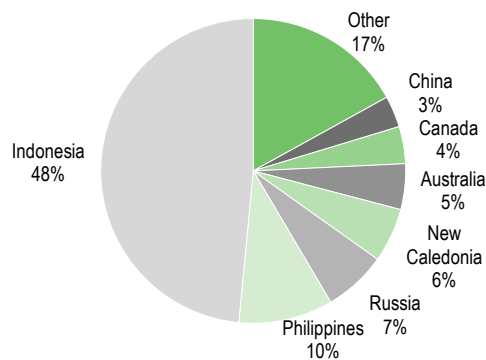
Are there alternatives?

Yes and no. Again, nickel chemistries currently dominate cathodes and the thrifting away from cobalt was done to some benefit to nickel.

How 'at risk' is supply?

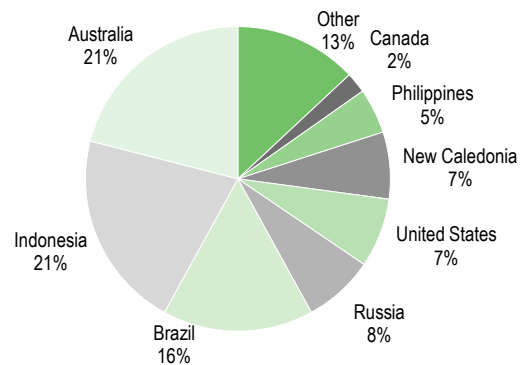
Very. Approximately 7% of global mine production in 2021 was accounted for by Russia, with the largest producers being Norilsk. Indonesia has also become a very fast source of supply growth in recent years, as low-grade nickel ores were used to produce refined nickel through the nickel pig-iron (NPI) production route. However, the critical issue is the availability of battery grade/class 1 nickel (which has a 99.8% purity minimum). Class 1 nickel is produced via more traditional processing routes, which account for around 50% of current supply. Nickel use in batteries typically begins with the production of precursor chemicals, mostly nickel salts or sulfates – a process that not only required high purity but also nickel in the form of powder or briquettes, further containing the linkages between production of nickel units and demand. Technologies other than NPI (for example pressure acid leaching of nickel laterites) have been technologically complex and economically challenging over the past two decades, so new sources of high-grade, economic nickel will be needed.

Exhibit 19: Global nickel mine production



Source: USGS, Edison Investment Research

Exhibit 20: Global nickel reserve distribution



Source: USGS, Edison Investment Research

Critical minerals companies

Exhibit 21: REE companies ranked by commodity and market cap

Company	Commodity	Market cap (US\$m)	Ticker	Listing	Country of operations	Description
MP Materials	REE	4603	MP	NYSE	US	US-based REE company (Mountain Pass mine in California). Strategy is to bring processing and ultimately magnet making back into the US from China
Lynas Rare Earths Ltd	REE	3946	LYC	ASX	Australia, Malaysia	Australian based mine/Malaysian processing REE firm, with one of the few non-Chinese large-scale value chains
Energy Fuels	Uranium, REE	782	EFR	TSX	Brazil	Recently acquired Bahia Project in Brazil, which will produce high-purity REE and NdPr
Arafura Resources	REE	652	ARU	ASX	Australia	Australia-based REE potential producer of mainly NdPr oxide and mixed middle-heavy rare earth (SEG/HRE) oxides
Alkane Resources	REE	288	ALK	ASX	Australia	Alkane's Dubbo project provides potential for REE and other critical minerals for high-tech and sustainable technologies
Hastings Technology Minerals	REE	200	HAS	ASX	Australia	Australia-based REE company developing the Yangibana rare earths mine
Pensana Plc	REE	182	PRE	LSE	UK / Angola	UK-based REE company – planned refinery in the UK and Longonjo neodymium and praseodymium project in Angola producing magnet metal oxides
Australian Strategic Materials	REE	138	ASM	ASX	Australia, Korea	Australia-based potential producer of REE, critical minerals and high-tech metals including NdPr
Peak Rare Earths	REE	67	PEK	ASX	Tanzania	Australian listed REE company with focus on its Ngualla Rare Earths Project in Tanzania and potential UK processing in Teeside
Rainbow Rare Earths	REE	59	RBWR	LSE	South Africa	Guernsey-based mining company focused on REE, originally at the Gakara mine in Burundi but increasingly focused on the Phalaborwa Project in South Africa
Vital Metals	REE	56	VML	ASX	Canada, Tanzania	Canada's first, and North America's second REE miner of both light and heavy rare earths at its Nechalacho mine
Ucore Rare Metals	REE, nickel, cobalt, lithium	52	UCU	TSXV	US	Canada-based, REE developer targeting both heavy and light REE at the Bokan-Dotson Ridge Rare Earth Element Project in south-east Alaska
Aclara Resources	REE	54	ARA	TSX	Chile	Chile-based REO developed targeting production from ionic clays
Mkango Resources	REE	37	MKA	LSE	Republic of Malawi (Africa)	Canada-based REE company focusing on the Songwe Hill deposit in Malawi. Strategy is to develop new sustainable primary and secondary sources of neodymium, praseodymium, dysprosium and terbium

Source: Refinitiv. Note: As at 27 March 2023.

Exhibit 22: Lithium companies ranked by commodity and market cap

Company	Commodity	Market cap (US\$m)	Ticker	Listing	Country of operations	Description
Albemarle	Lithium	25,546	ALB	NYSE	US, China	Producer and marketer of specialty lithium products
SQM	Lithium	20,824	SQM	NYSE	Chile	Produces both lithium carbonate and lithium hydroxide
Ganfeng	Lithium	18,404	2460	SHE	China	China-based company engaged in the production and sales of lithium and lithium battery products
Mineral Resources	Lithium	9,786	MIN	ASX	Australia	Australia-based company with integrated supply of goods and services to the resource sector
Pilbara Resources	Lithium	6,853	PLS	ASX	Australia	Pure-play lithium Australia-based company
Allkem Ltd	Lithium	4,296	AKE	ASX	Australia	Produces and processes lithium chemicals from brine, hard-rock and lithium hydroxide
Livent	Lithium	3,720	LTHM	NYSE	Argentina	Fully integrated lithium company, range of products, primarily lithium-based batteries
Sigma Lithium	Lithium	3,591	SGML	NYSE	Brazil	Canada-based company which owns 100% of four mineral properties in Brazil
Lithium Americas	Lithium	3,128	LAC	TSX	Argentina	Canada-based resource company with projects in Argentina and the US
Liontown	Lithium	2,227	LTR	ASX	Australia	Australia-based company, developing and supplying battery minerals for EV and energy storage
Sayona Mining Ltd	Lithium	1,091	SYA	ASX	Canada, Australia	Emerging leader in the supply of lithium for North America's electrification
Piedmont Lithium	Lithium	985	PLL	ASX	US	Engaged in building an integrated lithium business providing lithium hydroxide
Core Lithium	Lithium	961	CXO	ASX	Australia	Australia-based company focused on the development of its Finnis Lithium project
American Lithium Corp	Lithium	507	LI	TSXV	US	Canada-based exploration and development-stage company engaged in lithium projects
Vulcan Energy	Lithium	505	VUL	ASX	Germany	Australia-based company developing a combined geothermal and lithium extraction project in Germany
Ioneer Ltd	Lithium	562	INR	ASX	US	Lithium-boron producer – clean tech, EVs and renewable energy
Atlantic Lithium	Lithium	542	ALLA	LSE	Ghana, Cote d'Ivoire	Australia-based company engaged in developing lithium assets in West Africa
Frontier Lithium Inc	Lithium	484	FL	TSXV	Canada	Battery-grade lithium hydroxide and lithium salts – electric vehicles and energy storage
Lake Resources	Lithium	391	LKE	ASX	Argentina	Australia-based company engaged in exploring and developing lithium brine projects in Argentina.
Leo Lithium	Lithium	376	LLL	ASX	Mali	Australia-based company focused on the development of the Goulamina Lithium project
Li-FT Power Ltd	Lithium	221	LIFT	CNSX	Canada	Canada-based company focused on lithium pegmatite projects located in Canada
Galan Lithium	Lithium	192	GLN	ASX	Argentina	Australia-based company focused on its lithium brine projects in the Hombre Basin
Lithium Power International	Lithium	117	LPI	ASX	Chile, Australia	Pure-play Australia-based lithium company focused on the development of Chile's next sustainable high-grade lithium mine
E3 Lithium	Lithium	110	ETL	TSXV	Canada	Canada-based company aiming to power growing electrical needs
Jindalle Resources Ltd	Lithium, nickel	89	JRL	ASX	US	Australia-based company with a diverse portfolio of projects including lithium and nickel
Kodal Minerals	Lithium	79	KOD	LSE	Mali	UK-based company focused on the development of its Bougouni Lithium Project
Green Technology Metals	Lithium	78	GT1	ASX	Canada	North American lithium-focused exploration and development company aiming to become a fully integrated lithium carbonate/hydroxide producer
CleanTec Lithium	Lithium	76	CTL	LSE	Chile	Jersey-based company advancing projects in Chile for battery grade carbon neutral lithium
European Metal Holdings	Lithium	75	EMHE	LSE	Czech Republic	Focused on advancing the Cinovec vertically integrated battery metals project
Lepidico	Lithium	53	LPD	ASX	Namibia / UAE	Australia-based company engaged in the development of sustainable lithium hydroxide
Lithium South	Lithium	40	LIS	TSXV	Argentina	Canada-based company focused on developing the Hombre Muerto North Project
Bradda Head Lithium	Lithium	25	BHL	LSE	US	Lithium exploration company that owns 100% stake in lithium brine, pegmatite and clay projects located in the lithium belt in the US
Vision Lithium	Lithium	19	VLI	TSXV	Canada	Exploration company focused on battery mineral assets
Battery Age Minerals	Lithium	17	BM8	ASX	Canada	Australia-based, lithium focused for batteries

Source: Refinitiv. Note: As at 27 March 2023.

Exhibit 23: Nickel/cobalt companies ranked by commodity and market cap*

Company	Commodity	Market cap (US\$m)	Ticker	Listing	Country of operations	Description
CMOC Group	Cobalt	17,542	603993	SSE	The DRC	CMOC is the second largest cobalt producer globally with its mine in the DRC mainly producing cobalt hydroxide
Nickel Industries	Nickel	1,738	NIC	ASX	Indonesia	Australia-based company emerging as a globally significant, low-cost producer of NPI
Horizonte Minerals	Nickel	468	HZM	AIM	Brazil	UK-based nickel development company also listed on TSX
Centaurus Metals Ltd	Nickel	251	CTM	ASX	Brazil	Near-term development of the Jaguar Nickel Sulphide Project
PolyMet Mining Corp	Nickel	219	POM	TSX	US	Mine development company engaged in copper, nickel and precious metals
The Metals Company	Nickel, cobalt	215	TMC	NYSE	International Seabed	TMC is a deep-sea minerals exploration company focused on the processing and refining of polymetallic nodules (containing high grades of nickel, copper, cobalt and manganese)
Panoramic Resources	Nickel, cobalt	197	PAN	ASX	Australia	Australia-based base metal mining and exploration with its assets leveraging the nickel, copper and cobalt markets
Jervois	Nickel, cobalt	164	JRV	ASX	US, Finland, Brazil, Australia	Australia-based supplier of sourced cobalt and nickel for both the battery and chemical market
Sherritt	Nickel, cobalt	147	S	TSX	Cuba	Canada-based miner and refiner of nickel and cobalt for the EV market
Canadian Nickel Company	Nickel, cobalt	141	CNC	TSXV	Canada	Supply for EVs, green energy and stainless-steel markets
Cobalt Blue Holdings	Cobalt	84	COB	ASX	Australia	Australia-based cobalt miner supplying battery-ready cobalt for renewable energy storage and EVs
FPX Nickel Corp	Nickel	82	FPX	TSXV	Canada	Canada-based nickel mining company (in the form of nickel-iron alloy – awaruite)
Electra Battery Materials	Cobalt	65	ELBM	TSXV	US	Its Iron Creek project is one of the only primary cobalt-copper deposits in the United States – supporting the development of the EV supply chain
Ardea Resources Ltd	Nickel, cobalt	55	ARL	ASX	Australia	Australia-based battery mineral company
Alliance Nickel	Nickel, cobalt	42	AXN	ASX	Australia	Focused on becoming a supplier on battery-grade nickel and cobalt products
Technology Minerals	Cobalt, lithium, nickel	14	TM1	LSE	Cameroon, Canada,	UK-based company which extracts raw materials required for Lithium-ion cathodes
Cruz Battery Metals	Cobalt, lithium	11	CRUZ	CNSX	Canada	Canada-based company focused on acquiring and developing battery metal projects in North America

Source: Refinitiv as at 27 March 2023. *Note, we have excluded nickel/cobalt operations within the major miners.

Exhibit 24: Graphite companies ranked by commodity and market cap

Company	Commodity	Market cap (US\$m)	Ticker	Listing	Country of operations	Description
Syrax Resources	Graphite	688	SYR	ASX	Mozambique	Production of natural graphite products as well as anode materials from flake graphite
Talga Group	Graphite, cobalt, lithium	358	TLG	ASX	Sweden / Germany / UK	Battery company engaged in the production of battery anodes and graphene additives - battery metals projects in Sweden containing cobalt and lithium projects
Nouveau Monde Graphite	Graphite	253	NOU	TSXV	Canada	Mines high-purity flake graphite concentrate and has a battery materials plant in Quebec
NextSource Materials	Graphite	203	NEXT	TSX	Madagascar	Late-stage mine development of the full feasibility Molo project containing flake graphite deposits
Graphite One	Graphite	133	GPH	TSXV	Canada	Anode material miner for lithium-ion EV battery market and energy storage systems
Black Rock Mining	Graphite	85	BKT	ASX	Tanzania	Australia-based company hosting one of the largest JORC-compliant flake graphite resources globally at Mahenge in Tanzania
Northern Graphite Corp	Graphite	46	NGC	TSXV	Namibia, Canada	Canada-based acquisition, exploration, development company producing graphite (natural flake) and other battery mineral properties
Gratomic	Graphite	34	GRAT	TSXV	Canada, Namibia,	Canada-based junior exploration company with aim to deliver natural graphite for the EV market
Tirupati Graphite	Graphite	33	TGRT	LSE	Madagascar, India	Specialist in graphite and graphene
Volt Resources	Graphite	26	VRC	TSXV	Tanzania, Guinea, Ukraine	Australia-based graphite producer/developer of battery-ready anode materials for lithium-ion batteries
Mason Graphite	Graphite	25	LLG	TSXV	Canada	Canada-based mining and mineral processing company focused on the production and transformation of natural graphite
Leading Edge Materials Corp	Graphite, nickel, cobalt	20	LEM	TSXV	Sweden, Romania	Focused on developing projects in the EU for materials that power green energy
Lomiko Metals	Graphite, lithium	6	LMR	TSXV	Canada	Developing projects for both graphite and lithium in Quebec

Source: Refinitiv. Note: As at 27 March 2023.

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