Global Critical Minerals Outlook 2024

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Abstract

Critical minerals, which are essential for a range of clean energy technologies, have risen up the policy agenda in recent years due to increasing demand, volatile price movements, supply chain bottlenecks and geopolitical concerns. The dynamic nature of the market necessitates greater transparency and reliable information to facilitate informed decision-making, as underscored by the request from Group of Seven (G7) ministers for the IEA to produce medium- and long-term outlooks for critical minerals.

The Global Critical Minerals Outlook 2024 follows the IEA's inaugural review of the market last year. It provides a snapshot of industry developments in 2023 and early 2024 and offers medium- and long-term outlooks for the demand and supply of key energy transition minerals based on the latest technology and policy trends.

The report also assesses key risks to the reliability, sustainability and diversity of critical mineral supply chains and analyses the consequences for policy and industry stakeholders. It will be accompanied by an updated version of the Critical Minerals Data Explorer, an interactive online tool that allows users to explore the latest IEA projections.

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Executive summary

Executive summary

Fast-growing critical minerals markets remain turbulent, with prices falling sharply in 2023 following two years of dramatic increases. Battery materials saw particularly large declines with lithium spot prices plummeting by 75% and cobalt, nickel, and graphite prices dropping by 30-45%. The IEA Energy Transition Mineral Price Index, which tracks a basket price of copper, major battery metals and rare earth elements, tripled in the two years following January 2020, but relinquished most of the increase by the end of 2023 – although copper prices remained at elevated levels.

Demand growth has remained robust. Demand for critical minerals experienced strong growth in 2023, with lithium demand rising by 30%, while demand for nickel, cobalt, graphite and rare earth elements all saw increases ranging from 8% to 15%. Clean energy applications have become the main driver of demand growth for a range of critical minerals. Electric vehicles (EVs) consolidated their position as the largest-consuming segment for lithium, and increased their share considerably in the demand for nickel, cobalt and graphite.

The main reason for price declines has been a strong increase in supply and ample inventories of technologies made with critical minerals. From Africa to Indonesia and the People's Republic of China (hereafter "China"), the ramp-up of new supply outpaced demand growth over the past two years. Together with an inventory overhang in the downstream sector (e.g. battery cells, cathodes) and a correction of overly steep price rises in 2021-2022, this produced downward pressure on prices.

Clean energy deployment continues to advance in all our scenarios for the future, including a strong growth story for EVs. Following the 75% growth in deployment in 2023, solar PV and wind account for the majority of capacity additions in every region in all IEA scenarios. This is accompanied by a substantial expansion of electricity networks, pushing up demand for copper and aluminium. Electric car sales neared 14 million in 2023, a 35% year-on-year increase, and continued growth is projected as major markets progress and adoption increases in emerging economies. In a scenario that limits global warming to 1.5 °C (the Net Zero Emissions by 2050 [NZE] Scenario), the sales share of electric cars rises from 18% today to 65% in 2030, pushing up demand for batteries by a factor of seven to 6 TWh in 2030. Electric cars are the major source of demand for batteries, but battery storage for the power sector exhibits faster growth.

Today's well-supplied market may not be a good guide for the future, as demand for critical minerals continues to rise. Just as clean energy deployment expands, so too does demand for critical minerals. Mineral demand for clean energy technologies doubles between today and 2030 in a scenario that reflects today's policy settings, the Stated Policies Scenario (STEPS). It is even higher in a scenario that meets all national energy and climate goals in full, the Announced Pledges Scenario (APS), and it almost triples by 2030 and quadruples by 2040 in the NZE Scenario, reaching nearly 40 Mt. Lithium sees the most rapid growth in demand, due to rising EV battery needs. In the NZE Scenario, for example, it increases by a factor of nine to 2040. In terms of production volume, copper – which connects a more electrified energy system – has by far the largest increase. Graphite demand almost quadruples by 2040 in the NZE Scenario, while demand for nickel, cobalt and rare earth elements doubles.

Strong growth in demand produces a major uptick in the overall value of critical minerals markets. The combined market value of key energy transition minerals – copper, lithium, nickel, cobalt, graphite and rare earth elements – more than doubles to reach USD 770 billion by 2040 in the NZE Scenario. At around USD 325 billion, today's aggregate market value of key energy transition minerals aligns broadly with that of iron ore. By 2040, copper on its own attains that scale.

The benefits of market expansion are shared across different regions, especially for mining. Latin America captures the largest amount of market value for mined output with around USD 120 billion by 2030. Indonesia sees the fastest growth, doubling its market value by 2030 due to its burgeoning nickel production. Africa witnesses a 65% increase in market value by 2030. Nearly 50% of the market value from refining is concentrated in China by 2030. China also sees a rise in market value for mined materials with its growing copper and lithium production.

The recent fall in prices has affected investments in new mineral supply, but they are still growing. Increases in 2023 were smaller than those seen in 2022, but investment in critical mineral mining nonetheless grew by 10%. Investment by lithium specialists saw a sharp rise of 60%, despite weak prices. Exploration spending also rose by 15%, driven by Canada and Australia. Venture capital spending increased by 30%, with significant growth in battery recycling offsetting reduced investment in mining and refining start-ups. China's spending on and acquisition of overseas mines has grown significantly in the past ten years reaching record levels of USD 10 billion in the first half of 2023 with a particular focus on battery metals such as lithium, nickel and cobalt.

Our projections show a mixed picture for future supply-demand balances. Based on a detailed review of all announced projects, we have constructed two supply scenarios. The base case includes production from existing assets and those under construction, along with projects that have a high chance of moving ahead. The high production case adds in projects, which are at a reasonably advanced stage of development, seeking financing and/or permits. Using the APS as a benchmark, the situation in 2035 looks as follows:

- There is a significant gap between prospective supply and demand for copper and lithium: Anticipated mine supply from announced projects meets only 70% of copper and 50% of lithium requirements.

- Balances for nickel and cobalt look tight relative to confirmed projects, but better if prospective projects are included (our high production case).
- Graphite and rare earth elements may not face supply volume issues but are among the most problematic in terms of market concentration: over 90% of battery-grade graphite and 77% of refined rare earths in 2030 originate from China.

The NZE Scenario necessitates further project developments across most minerals.

Our analysis of announced projects shows limited progress in diversifying supply. The geographical concentration of mining operations is set to rise further or remain high over the projection period in the base case. The situation improves somewhat in the high production case, indicating that many potential projects being developed in geographically diverse regions are not among the front-runners for development. For refined materials, the shares of the top three producing nations have all increased since 2020, with the trend most pronounced for nickel and cobalt. Announced projects indicate that refined material production is set to remain highly concentrated in a few countries. Between now and 2030, some 70-75% of projected supply growth for refined lithium, nickel, cobalt and rare earth elements comes from today's top three producers. For battery-grade spherical and synthetic graphite, almost 95% of growth comes from China. These high levels of supply concentration represent a risk for the speed of energy transitions, as it makes supply chains and routes more vulnerable to disruption, whether from extreme weather, trade disputes or geopolitics.

Analysis based on asset ownership reveals a slightly different picture. The concentration in the mining sector looks different if viewed through the lens of asset ownership, with US and European companies playing a major role for copper and lithium supplies whereas Chinese companies have a greater role for nickel and cobalt production, despite these minerals being mined elsewhere (e.g. Indonesia for nickel and the Democratic Republic of the Congo for cobalt).

High market concentration means there is a risk of significant shortfalls in supply if, for any reason, supply from the largest producing country is interrupted. This "N-1" analysis is a typical measure of the resilience of any system and reveals significant vulnerabilities. If the largest supplier and its demand is excluded, then available "N-1" supply of all key energy transition minerals would fall significantly below material requirements. The situation is most pronounced for graphite where the available "N-1" supply covers only 10% of the N-1 material requirements – significantly below the minimum non-single-origin threshold of 35% proposed in the EU Critical Raw Materials Act. This indicates that without urgent efforts to expedite the development of projects, achieving announced diversification goals will be highly challenging.

Today's price declines are a double-edged sword – a boon for clean energy deployment but a bane for critical mineral investment and diversification. Lower prices have been good news for consumers and for affordability, bringing clean technology costs back on a downward trajectory, including the 14% reduction in battery prices in 2023. However, falling prices also make spending to ensure reliable and diversified supply less appealing to investors. This price effect has had the biggest consequences in new and emerging resource holders; in the case of nickel, three-quarters of operating or potential projects that are at risk are outside the top three producers.

Our first-of-its-kind risk assessment reveals potential areas of weakness for each mineral in supporting energy transition goals. The *Outlook* includes a new risk assessment framework for key energy transition minerals, across four major dimensions – supply risks, geopolitical risks, barriers to respond to supply disruptions, and exposure to environmental, social and governance (ESG) and climate risks. Overall, lithium and graphite show the highest risk scores. Lithium and copper are more exposed to supply and volume risks whereas graphite, cobalt, rare earths and nickel face more substantial geopolitical risks. Most minerals are exposed to high environmental risks. For example, today's refining operations occur in places where grids tend to have a higher carbon intensity, relying mostly on coal-based electricity.

Some USD 800 billion of investment in mining is required to get on track for a 1.5 °C scenario to 2040. In the APS, approximately USD 590 billion is required over the same period. These increases need to be made in a way that fosters a more diversified array of supply sources in the future. Financing diversified critical mineral supply chains faces numerous challenges, such as cost inflation, long-term price uncertainty and limited value placed on diversification by consumers. This requires specific policy measures to reinforce the investment case for supply chain diversification. Enhancing market transparency can also help, from pricing – with benefits to be drawn from efficient price discovery mechanisms and financial tools to hedge risks – to information, with a strong need for increasing the availability of reliable data on consumption, supply and trade.

Stepping up efforts to recycle, innovate and encourage behavioural change is vital to ease potential strains on supply. In the case of lithium, the combination of right sizing EV batteries, alternative chemistries and recycling could reduce demand by 25% in 2030 in the NZE Scenario, saving an amount roughly equivalent to today's production. Recycling rates for many materials have exhibited limited growth in the past. In the NZE Scenario, however, this needs to change, with growing policy attention to stepping up rates of collection and reprocessing. Recycled quantities of copper and cobalt could reduce 2040 primary supply requirements by 30%, and 15% for lithium and nickel. Without the uptake of recycling and reuse, mining capital requirements would need to be one-third higher.

New supplies must not come at the cost of local communities or the environment. Our systematic ESG performance tracking paints a mixed picture. The industry is making progress on worker safety, gender balance, community investment and renewable energy uses, but the same cannot be said for waste generation, emissions and water consumption and discharge, suggesting ample scope for improvement. The benefits associated with mineral production, such as revenue and jobs, have to be felt by producer countries and communities. Voluntary sustainability standards can help actors improve ESG performance, but greater transparency, due dilligence, harmonised approaches to credibility and appropriate incentives are needed to tap their full potential.

Introduction

Introduction

After the relentless surge in prices since 2021, the critical minerals market underwent another tumultuous year in 2023. Prices for most materials experienced a significant decline, relinquishing most of the increases accumulated over the past two years. Prices for battery metals saw particularly steep reductions due to an inventory overhang in the downstream sector, a slight easing in the pace of demand growth and an increase in overall supply.

While immediate concerns appear to have eased, the risks of market tightness and price volatility remain ever-present as countries pursue decarbonisation goals. Moreover, the geopolitical context is increasingly complex, highlighted by a series of trade restriction measures in 2023, including gallium, germanium, graphite and technologies related to rare earth elements. Low material prices helped to put the costs of clean energy technologies back on a downward trajectory, but they present a challenge for efforts to diversify supply, given the financial difficulties that they pose for new and emerging producers. The imperative to bolster the diversity and resilience of critical mineral supplies remains at the top of the policy agenda.

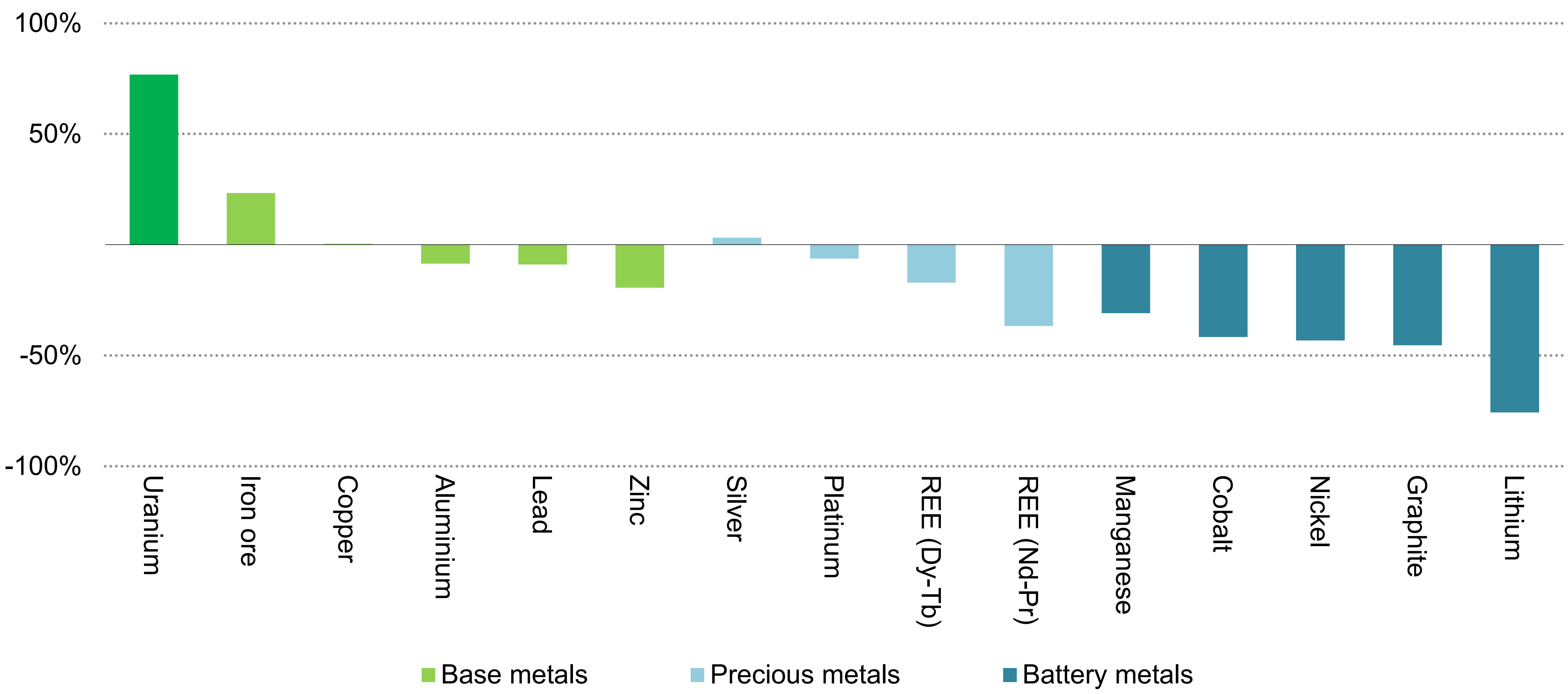
In line with new mandates approved by the 2024 Ministerial meeting, the IEA has been working together with countries and industry to address these emerging challenges and ensure reliable and sustainable supplies of critical minerals. On 28 September 2023, the IEA hosted the first-ever Critical Minerals and Clean Energy Summit at the IEA headquarters in Paris. Almost 50 countries, including key producing and consuming nations around the world, came together with around 40 business leaders, investors, heads of international organisations and civil society organisations to share their experiences and discuss effective courses of action to ensure rapid and secure energy transitions. Chief among various desired actions was the need for robust market monitoring and outlooks that can help bring a clear understanding of today's market situation and anticipate potential risks in the medium to long term.

Earlier in 2023, the Group of Seven (G7) ministers asked the IEA to play a strengthened role in safeguarding minerals security in its G7 Five-Point Plan, through producing medium- and long-term outlooks for critical minerals and introducing the IEA Voluntary Critical Minerals Security Programme.

This report, following the inaugural Critical Minerals Market Review 2023, responds to these growing needs for enhanced market transparency by reviewing latest market movements, examining the prospects for future mineral demand and supply, and assessing potential risks along the supply chain of key commodities.

Prices for minerals and metals experienced a widespread decline in 2023, with battery metals experiencing particularly sharp reductions

Change in selected commodity prices in 2023



Notes: REE = rare earth elements; Dy-Tb = dysprosium and terbium; Nd-Pr = neodymium and praseodymium. Change in prices between December 2022 and December 2023.

Sources: IEA analysis based on Bloomberg and S&P Global.

Scope of the analyses and scenarios

The report considers a wide range of “critical minerals” that play a vital role in clean energy applications, as indicated in the Annex. The main focus is on “key energy transition minerals” (also referred to as “focus minerals”) such as **copper, lithium, nickel, cobalt, graphite and rare earth elements**. However, the report also discusses trends for other important materials such as aluminium, manganese, phosphate, platinum group metals and uranium as relevant.

Our assessment of mineral demand in the clean energy sector includes demand for low-emissions power generation (solar PV, wind, hydro, nuclear and other renewables), electric vehicle batteries and battery storage, grid networks (transmission, distribution and transformer), and hydrogen (fuel cells and electrolyser) technologies.

Our forward-looking analysis is based on the three main IEA scenarios included in the World Energy Outlook 2023, updated for the latest data points.

- The **Stated Policies Scenario (STEPS)** provides a sense of the prevailing direction of travel for the energy system, based today’s policy settings. The STEPS is associated with a temperature rise of 2.4 °C in 2100 (with a 50% probability).
- The **Announced Pledges Scenario (APS)** assumes that governments will meet, in full and on time, all of the climate-related commitments that they have announced, including longer term net zero emissions targets and pledges in nationally determined contributions (NDCs). The APS is associated with a temperature rise of 1.7 °C in 2100 (with a 50% probability).
- The **Net Zero Emissions by 2050 (NZE) Scenario** charts a pathway for the global energy sector to achieve net zero CO_2 emissions by 2050 and limit the global temperature rise to 1.5 °C above pre-industrial levels in 2100 (with at least a 50% probability) with limited overshoot. The NZE Scenario also meets the key energy-related UN Sustainable Development Goals (SDGs) such as universal access to reliable modern energy services and major improvements in air quality.

Alongside the main scenarios, we explore some alternative cases reflecting key technological and behavioural uncertainties that could affect future material demand (see Annex).

Chapter 1 (Market review) offers a snapshot of industry developments in 2023 and early 2024. It describes the trends of clean energy technology deployment that drives the demand growth for critical minerals and reviews major production, investment and price trends. The chapter also discusses the latest policy developments and insights based on systematic tracking of the industry’s environmental, social and governance (ESG) performance.

Chapter 2 (Demand and supply outlook for key energy transition minerals) provides an outlook for demand and supply of key individual minerals and related market and policy issues. Following a brief review of mineral demand for clean energy technologies, the chapter provides projections for focus minerals including copper, lithium, nickel, cobalt, graphite and rare earth elements. It also reviews key trends for other important materials.

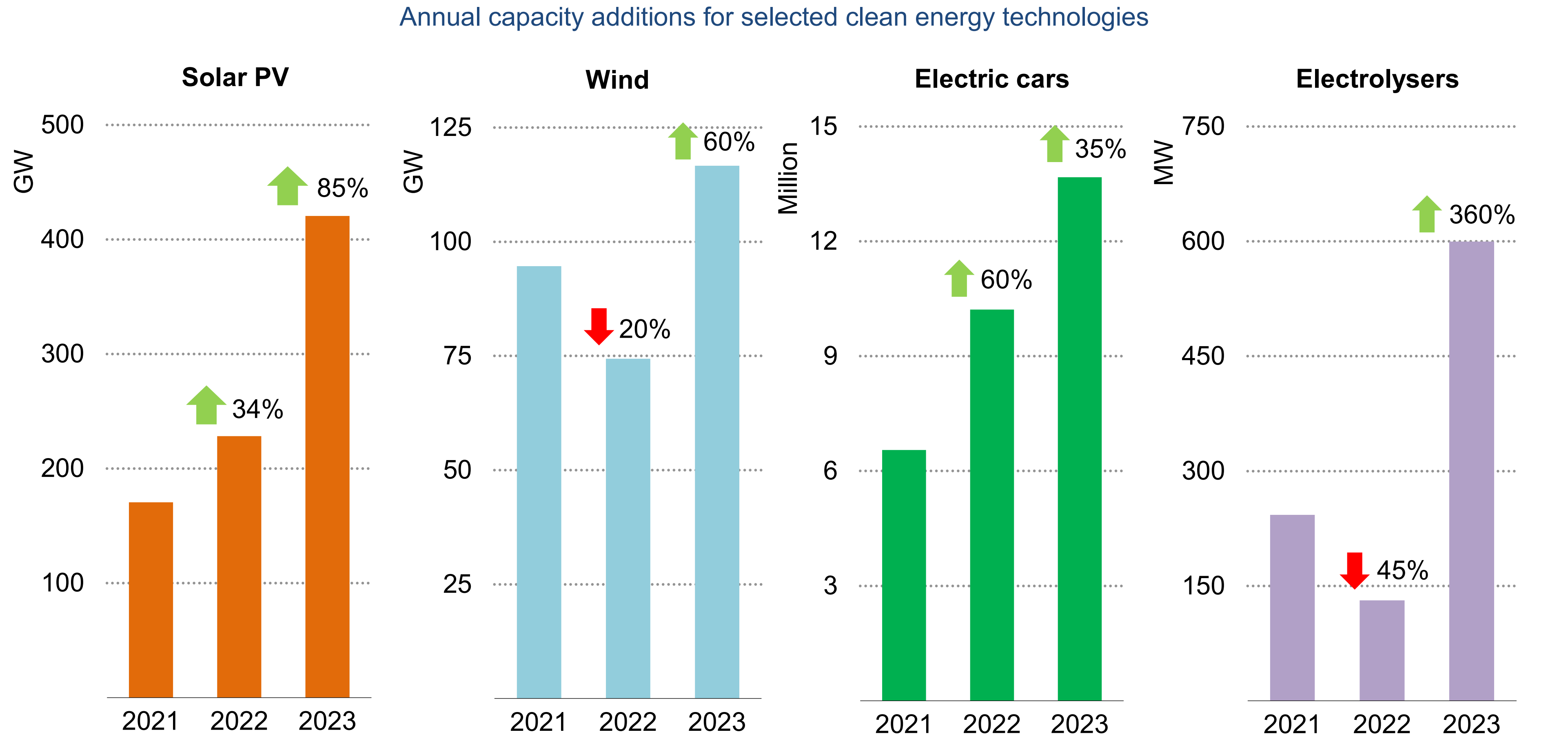
Chapter 3 (Clean energy transition risk assessment) contains structured “clean energy transition risk assessments” for the six focus minerals that cover supply risks, geopolitical risks, barriers to respond to disruptions, and exposure to ESG and climate risks.

Chapter 4 (Implications) presents the strategic implications of the scenario projections for policy and industry stakeholders seeking to promote reliable, sustainable and diversified supplies of critical minerals. The chapter considers four major issues such as i) investment in diversified supply; ii) recycling, innovation and behavioural change; iii) market transparency; and iv) sustainable and responsible supplies.

1. Market review

Clean energy deployment trends

Global clean energy deployment climbed to new heights in 2023



Sources: IEA (2024), Clean Energy Market Monitor – March 2024, and IEA (2024), Global EV Outlook 2024.

Clean energy deployment continues to soar, with China the main driving force

Global clean energy deployment scaled new heights in 2023, with annual additions of solar PV growing 85% and wind turbines growing 60%. The growth in clean energy deployment, however, remains concentrated in advanced economies and the People's Republic of China (hereafter "China"), with most developing economies lagging behind.

Solar PV

Global solar PV capacity additions for electricity generation broke a new record, reaching 420 GW in 2023. Solar PV alone accounted for three-quarters of renewable capacity additions worldwide. China alone accounted for 62% of the increase in global solar PV capacity. Despite the phase out of central government subsidies, the country commissioned as much solar PV in 2023 as the entire world did in 2022.

In the European Union (EU), annual solar PV additions rose by a quarter and reached a record level 52 GW in 2023. Following the Russian Federation's (hereafter "Russia") invasion of Ukraine, the EU member states improved the policy environment to accelerate renewables deployment, in part to help bring down natural gas consumption. This has led annual solar PV additions to double since 2021. In the United States (US), solar PV capacity additions increased 50% year-on-year following the easing of supply chain issues that slowed deployment in 2022. Federal tax incentives and state-level support have continued to drive both utility-scale and rooftop solar PV applications. India added only 12 GW of solar PV in 2023, one-third lower than in 2022. Nevertheless, in 2023 the government unveiled an objective to conduct annual auctions for 50 GW of renewable energy capacity that promises to accelerate deployment significantly.

Wind

Global wind capacity additions jumped by 60% in 2023 to break the record seen in 2020. Onshore wind projects accounted for over 85% of global wind deployment in 2023. China accounted for more than 60% of global wind expansion as the country almost doubled its additions compared with 2022.

In the European Union, wind additions increased by less than 10% in 2023, with onshore wind deployment slowing down. Developers have been facing multiple challenges, including rising equipment costs, inflation, and supply chain constraints, which have made them less eager to participate in competitive auctions. Most countries in Europe have introduced policies to address the challenges posed by slow and complex permitting procedures for wind projects. However, the impact of these policies will take time to be visible in deployment trends. In the United States, wind additions declined by more than a quarter in 2023. This was mainly due to prior uncertainty over the future of tax credits, prior to the adoption of the Inflation Reduction Act (IRA). Wind capacity additions are expected to increase significantly in the coming years thanks to the policy visibility provided by the IRA. In India, a larger number of projects awarded in previous years led annual deployment to increase by almost 50% in 2023.

Offshore wind growth has recovered from a major drop seen in annual additions in 2022. However, the offshore industry outside of China is facing challenges with investment costs today more than 20% higher than a few years ago. In 2023, developers cancelled or postponed 15 GW of offshore wind projects in the United States and the United Kingdom because pricing for previously awarded capacity no longer reflected prevailing project development costs.

Overall, the world is poised for a signficant acceleration in renewable capacity in the coming years driven by supportive policies in more than 130 countries. Renewables are expected to surpass coal to become the largest source of electricity generation by the mid-2020s. Substantial demand for materials such as copper, silicon and rare earth elements will be required to support the rapid deployment of renewable generation capacity. However, challenges such as high interest rates and low profitability persist. Policymakers need to address issues related to permitting and grid expansion to achieve the target of tripling global renewable capacity by 2030 that was agreed at the 28th Conference of the Parties (COP28).

Electrolysers

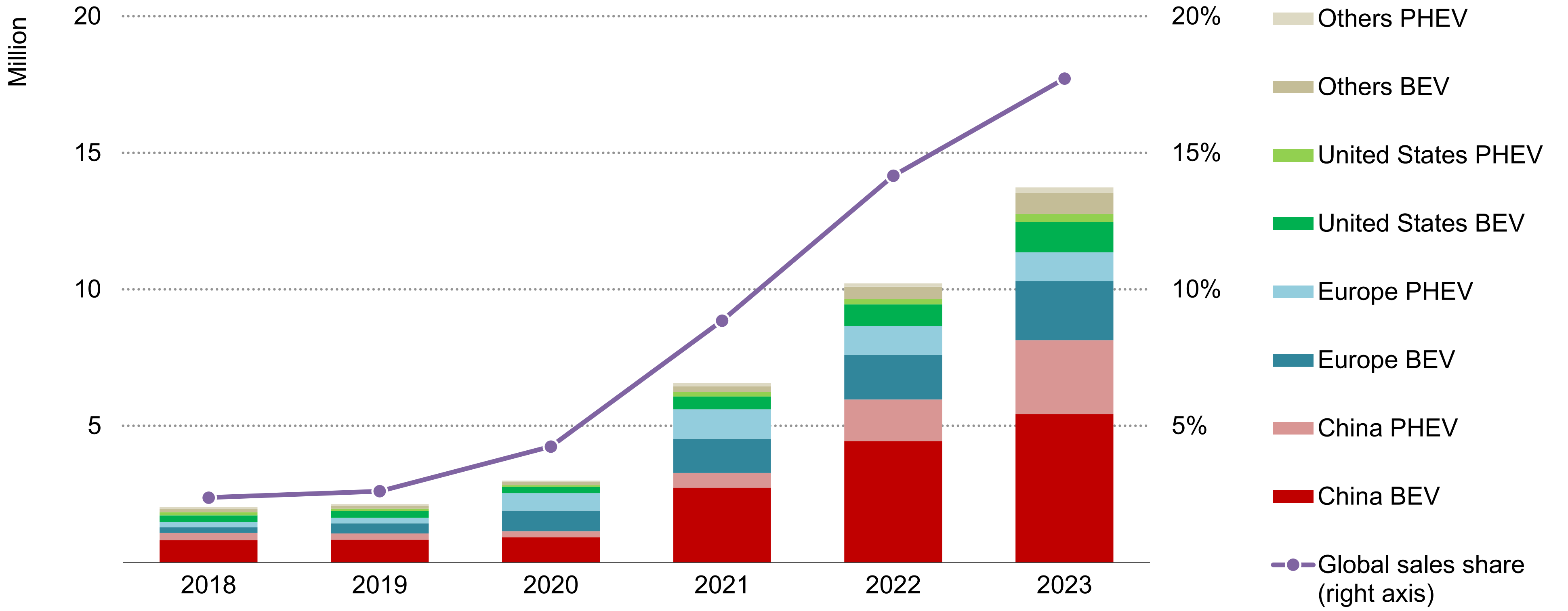
The growing markets for eletrolysers could push up demand for nickel, platinum group metals, zirconium and other minerals depending on the specific technology deployed. In 2023, global installed capacity of electrolysers for hydrogen production reached 1.3 GW, underpinned by a surge in annual additions to 600 MW. However, this is still far from the annual multi-gigawatt additions required to keep global climate goals within reach.

From less than 10% of global installed capacity in 2020, China has emerged as the leading region since 2021, reaching an installed capacity of more than 650 MW by the end of 2023. China now represents close to half of the global installed capacity. This transformation has been fuelled by the scaling up of project sizes by Chinese developers, with several projects now exceeding 100 MW in capacity. Consequently, China now hosts six of the world's largest operational electrolysis projects. The European Union accounted for around a third of global installed capacity in 2020, but has now ceded its leading position, with additions of around 70 MW in 2023. The United States emerged as the third-largest market, with additions exceeding 30 MW.

Demand uncertainty and lack of regulatory clarity, coupled with recent challenges such as inflation and slow implementation of support mechanisms are hindering faster adoption of electrolysers in other regions.

The growth story continued in 2023 for EVs

Electric car sales by mode and region



Note: BEV = Battery electric vehicle; PHEV = Plug-in hybrid electric vehicle.
Source: IEA (2024), Global EV Outlook 2024.

Growth in electric car sales remains robust as major markets progress and emerging economies ramp up

Electric car sales neared 14 million in 2023, a 35% year-on-year increase, and more than six times higher than five years earlier in 2018. Electric cars accounted for 18% of all car sales in 2023 up from 14% in 2022 and only 2% five years earlier, and nearly 95% of all sales were in China, Europe and the United States. These trends demonstrate robust growth in electric car markets as they become more mature, even if the growth in global electric car sales slowed somewhat compared with the 60% seen in 2022.

China is the world's largest electric car market with 8.1 million electric car sales and 60% of the global total in 2023, a share that has been increasing, up from 50% five years earlier in 2018. In 2023 more than one in three new car registrations in China was electric. The growth rate of electric car sales in China more than halved in 2023 to 35% from 80% in 2022. One of the critical reasons for this is that 2023 was the first year that the government provided no purchase subsidies for electric cars, with their phase-out in 2022. Therefore, a slowdown of electric car sales was expected. This is also coupled with relatively weak consumer sentiment. As the Chinese market matures, the industry is entering a phase of price competition and consolidation. To mitigate lower domestic demand, China exported 1.2 million electric vehicles (EVs) in 2023, an 80% increase from the previous year, with primary export markets being Europe and the Asia Pacific region including Thailand and Australia. In April, China removed down payment requirements for new car loans in an effort to stimulate consumer demand. In the first quarter of 2024 the year-on-year electric car sales growth rate in China increased to 36% compared with 27% in the same period last year. It is estimated that around 45% of all cars sold in China in 2024 could be electric.

Europe is the second-largest electric car market with almost 25% of global sales in 2023, reaching 3.2 million electric car sales. This year more than one in five cars sold in Europe was electric. Unlike China, Europe did not experience a slowdown as the growth rate of electric car sales slightly accelerated in 2023 to 20%, up from 15% in 2022. However, sales trends differed by country. In Germany the electric car sales share fell from 30% in 2022 to 25% in 2023 due to the sudden end of all EV subsidies in 2023, which were originally intended to apply until the end of 2024. Nevertheless, in the rest of Europe electric car sales shares increased, with the Netherlands reaching 30%, the United Kingdom and France 25%, and Sweden 60%.

In the United States electric car sales grew to 1.4 million in 2023, increasing by 40% compared with 2022, the fastest growth rate of the three largest regions, though the sales share of electric cars reached only 10%. The United States experienced a slight slowdown compared with the 55% rise in 2022, but growth in sales remained strong, with the IRA having supported sales despite some concerns about domestic component requirements hindering deployment. The revision of eligibility criteria for IRA tax credits in 2023 meant several popular vehicles were covered, and the Tesla Model Y increased its sales by 50% year-on-year. In 2024 new guidance significantly reduced the number of eligible vehicles for tax credits.

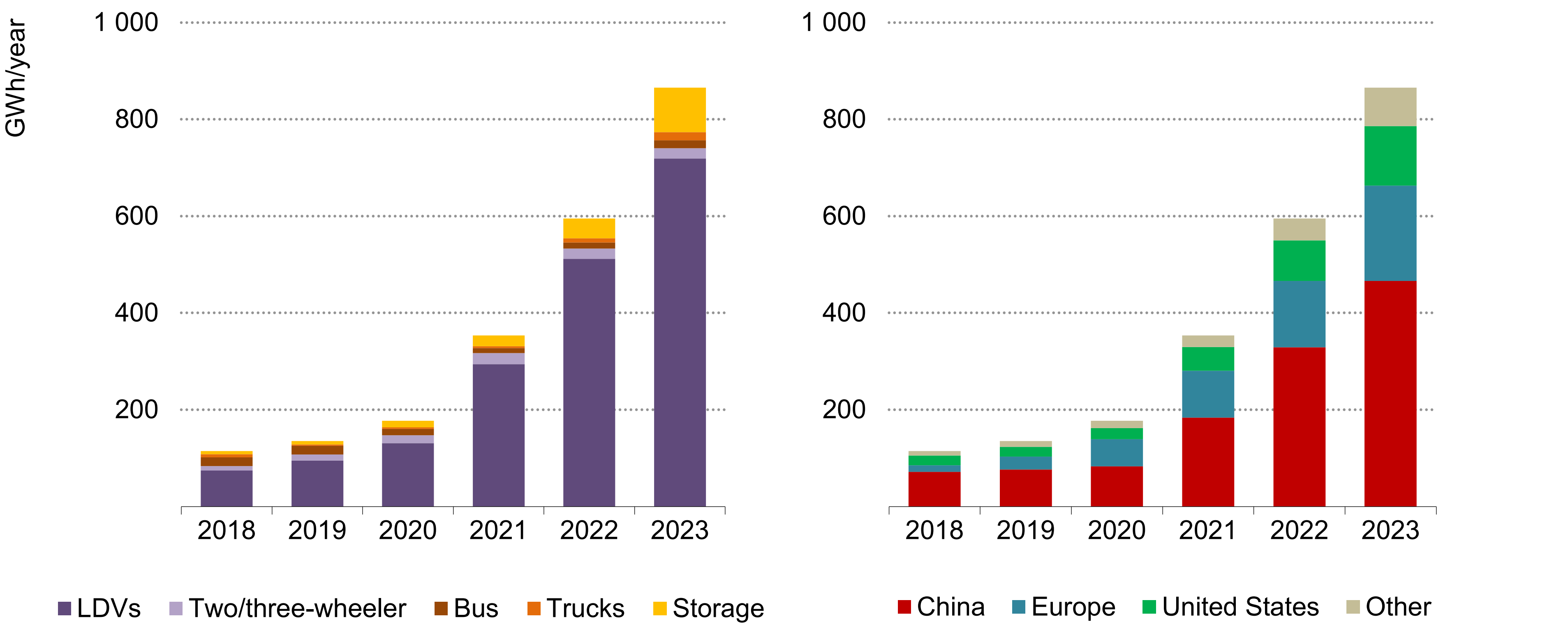
In the rest of the world, total electric car sales grew by 70% and sales almost reached 1 million electric cars. India experienced 70% year-on-year growth, with sales of 80 000 vehicles, compared with just 10% growth for total car sales. In Thailand electric car sales increased more than fourfold, reaching 90 000 vehicles and a 10% market share, a particularly impressive achievement given that total car sales decreased from 2022 to 2023. Subsidies in both regions have facilitated demand growth though India is anticipated to reduce subsidy levels in 2024.

In both China and the United States, sales of plug-in hybrid electric vehicles (PHEVs) grew significantly faster than battery electric vehicles (BEVs) (55% against 40% for the United States and a remarkable 80% against 20% in China). As a result, the share of PHEVs in EV sales reached 33% in China, up from 25% in 2022, and 20% in the United States. Concerns about driving range and lack of sufficient charging infrastructure for BEVs appear to be the driving force. In China, this surge in PHEV demand suggest that the growing middle-class appear to be more concerned about range going forward, marking a break from the past where relatively low-range BEVs were popular. The average battery size for PHEVs in China is around 50% higher than in Europe. A recent trend in China has been towards extended-range EVs (EREVs), which have an electric powertrain but also have a combustion engine able to recharge the battery. EREVs have a battery around twice the size of a typical PHEV, enabling real-world electric range of around 150 km, more than double that of conventional PHEVs. In 2023 EREVs accounted for a quarter of Chinese PHEV sales, a 10% increase from 2022, although EREVs have a negligible sale share outside of China. Europe, however, saw significantly higher growth in BEV sales with over 30% growth year-on-year compared with a small drop in PHEV sales in 2023.

Although growth rates in EV sales are slowing, early signs from 2024 indicated that sales remain generally strong. As the market matures and subsidies are phased out, growth rates may decrease somewhat. However, robust growth in EV sales is still expected to continue in the near and long term, supported by ongoing policy momentum, major increases in manufacturing capacity, cost declines and expanded adoption in developing economies.

Battery demand is dominated by electric cars, although storage is the fastest growing source of demand

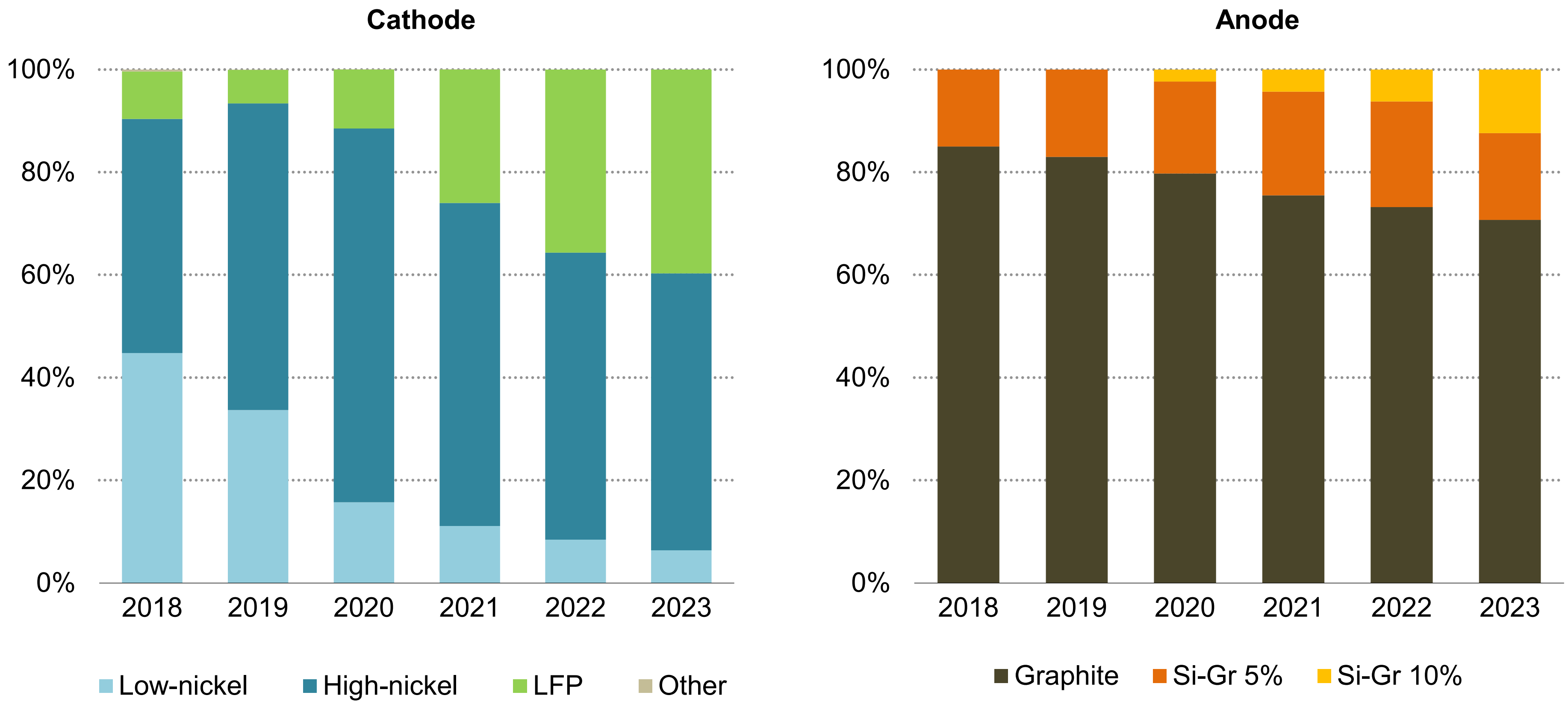
EV and storage battery demand by mode and region, 2018-2023



Note: LDVs = light-duty vehicles.
Source: IEA analysis based on EV Volumes.

The market share of LFP chemistries rose to 40% of electric car sales while silicon is gaining ground in graphite anodes

Electric car battery cathode and anode chemistries sales share, 2018-2023

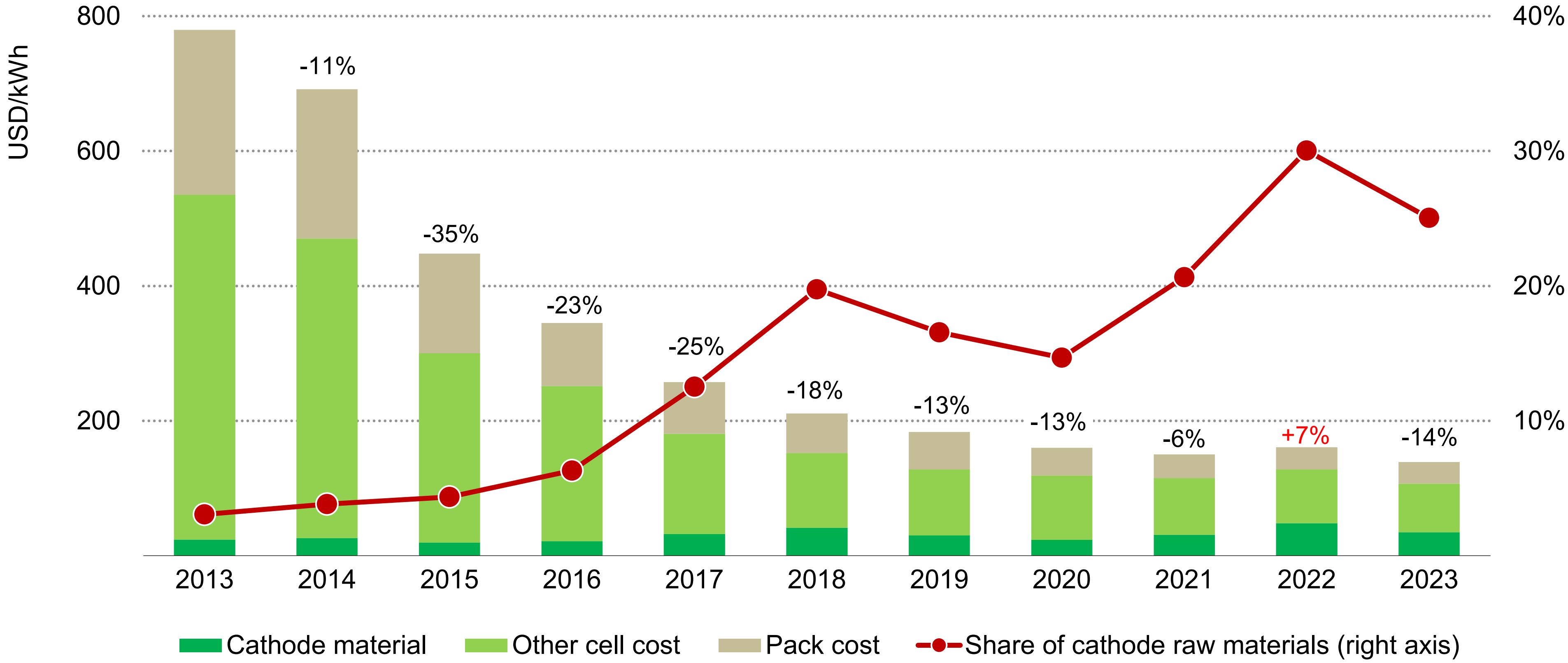


Notes: NMC = lithium nickel manganese cobalt oxide. Low-nickel includes: NMC333 and NMC532. High-nickel includes: NMC622, NMC721, NMC811, NCA and NMCA. LFP = lithium iron phosphate; Si-Gr = Silicon-doped graphite with % of silicon content. Sales share is based on capacity.

Source: IEA analysis based on EV Volumes and BloombergNEF.

Battery pack prices have dropped with falling critical minerals prices

Average lithium-ion battery pack price and share of cathode raw material cost, 2013-2023



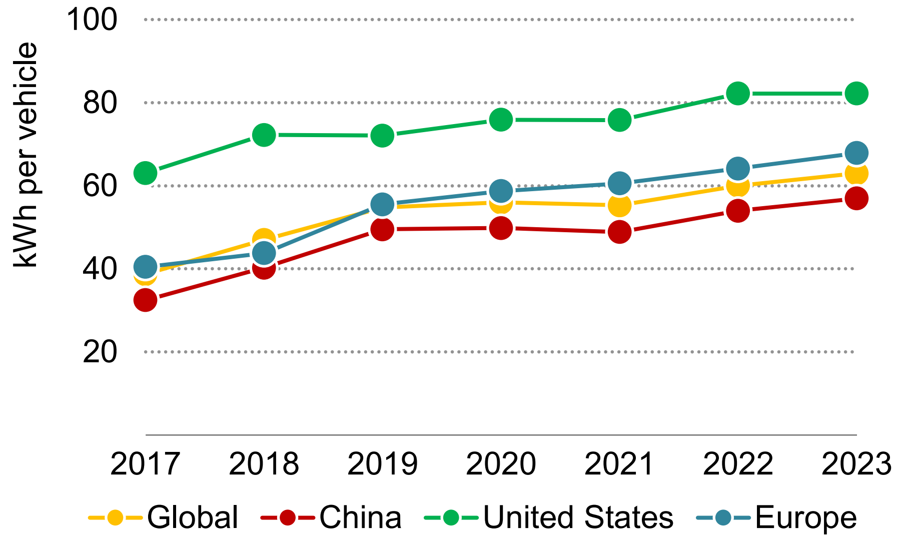
Notes: Cathode material costs include lithium, nickel, cobalt and manganese. Other cell costs include costs for anode, electrolytes, separator and other components as well as costs associated with labour, manufacturing and capital depreciation. Percentages on bars show year-on-year total pack price change. Analysis includes all cathode chemistries and global chemistry sales shares.
Source: IEA analysis based on BloombergNEF (2024).

Batteries: The rise and rise of LFP

In 2023, global battery demand from EVs and storage reached 865 GWh in 2023, a 45% year-on-year increase. This was primarily driven by sales of electric cars, which were responsible for 85% of global demand. The annual growth rate for battery demand from electric cars, buses and trucks slowed in 2023 to 40%, compared with 75% in 2022, in line with broader sales trends, although annual demand growth from two- or three-wheelers increased. Battery storage demand experienced the most impressive rise, more than doubling from the 2022 level, bringing its share in total EV and storage demand up to 10%. Given that growth rates for battery storage had almost doubled in 2021, this represents a remarkable surge in utility-scale and behind-the-metre storage deployment.

China was the largest source of battery demand in 2023 with 55% of the global total, followed by Europe with around a quarter and the United States with 15%, in each case dominated by EV sales. Battery demand in China grew by over 40% in 2023; this was half the rate seen in 2023 despite a threefold rise in demand for storage deployment. Battery demand in Europe and the United States both grew by 45%, a higher rate than for electric car sales due to a combination of larger vehicle and battery sizes and higher rates of storage deployment.

Average passenger BEV battery size, 2017-2023



Alongside sales, the rise in battery sizes for EVs is a critical driver of growth in demand for batteries and for critical minerals. In most regions the average battery size for passenger BEVs has been increasing year-on-year, with the global average increasing more than 60% since 2017. The trend towards an increasing share of sport utility vehicles (SUVs) found in conventional car markets is being replicated in the EV market. Automakers are focusing on larger vehicles, which are typically more profitable, and consumers appear to have a strong appetite for larger vehicles and ranges, even if they are often beyond their requirements. All regions follow the same overall trend for increased battery sizes, but there are significant regional variations in absolute values. The average battery size in the United States is 30% larger than the global average, Europe is 10% larger while China is 10% smaller. This mirrors size trends in conventional vehicle sectors, and also shows the greater preference from consumers in the United States and Europe for higher range EVs.

Battery pack price trends

In 2023 average battery pack prices dropped 14% to a record low of USD 139/kWh. This was the largest price decrease since 2018, driven primarily by the fall in critical minerals prices, in combination with a surge in battery production capacity and slightly weaker demand than expected. This reinstates the trend of declining battery prices that was temporarily reversed in 2022 due to the exceptionally high prices of battery critical minerals. Cells now account for 80% of the total pack price, an increasing ratio partly due to the cell-to-pack (CTP) design innovation reducing dead weight in the pack and pack costs.

With decreasing manufacturing costs from economies of scale and innovation, critical minerals have been a growing share of the battery pack cost, leaving the battery pack price more susceptible to mineral price volatility. This was seen clearly in 2022 when cathode raw materials peaked at 30% of the total pack price before falling back to to 25% in 2023.

Battery chemistry trends

One of the most remarkable developments in the global battery sector in the last five years has been the resurgence of the lithium iron phosphate (LFP) cathode chemistry. With a lower energy density but more stable and lower-cost chemistry compared to the nickel-based chemistries, LFP was being phased out in favour of the significantly higher energy density nickel-based cathode chemistries. However, there has been a remarkable reversal of fortune since 2019. The fact that LFP contains no nickel or cobalt became an important asset that helped reduced exposure to high commodity prices. In addition, the emergence of CTP technology eliminated dead weight in the battery pack and enhanced the energy density of LFP. CTP was pioneered by BYD with the Blade battery. LFP has now become a major chemistry in 2023 with around 40% of electric car battery sales by capacity. Due to favourable patent agreements China had been the only country producing LFP batteries after 2010. However, the patents expired in 2022, which kick-started production plans outside China. Nevertheless, there are still major regional differences, less than 10% of total EV sales by capacity in the United States and Europe are LFP while two-thirds are LFP in China.

Another major recent innovation was the first fast charging LFP battery, Shenxing developed by CATL, capable of delivering 400km of range from a ten-minute charge. This is achieved through a new electrolyte and graded anode porosities among other innovations. The novel fast charging LFP battery will be utilised in EV vehicles this year, significantly increasing the attractiveness of LFP chemistries.

The other significant recent LFP innovation is the development and commercialisation of lithium manganese iron phosphate (LMFP), the upgraded version of LFP including manganese which increases its energy density. With CATL's M3P battery confirmed for use in six Chinese EV models and undergoing validation by Tesla for its Chinese Model 3, it is anticipated that LMFP will continue to take market share from nickel-based chemistries due to its increased range.

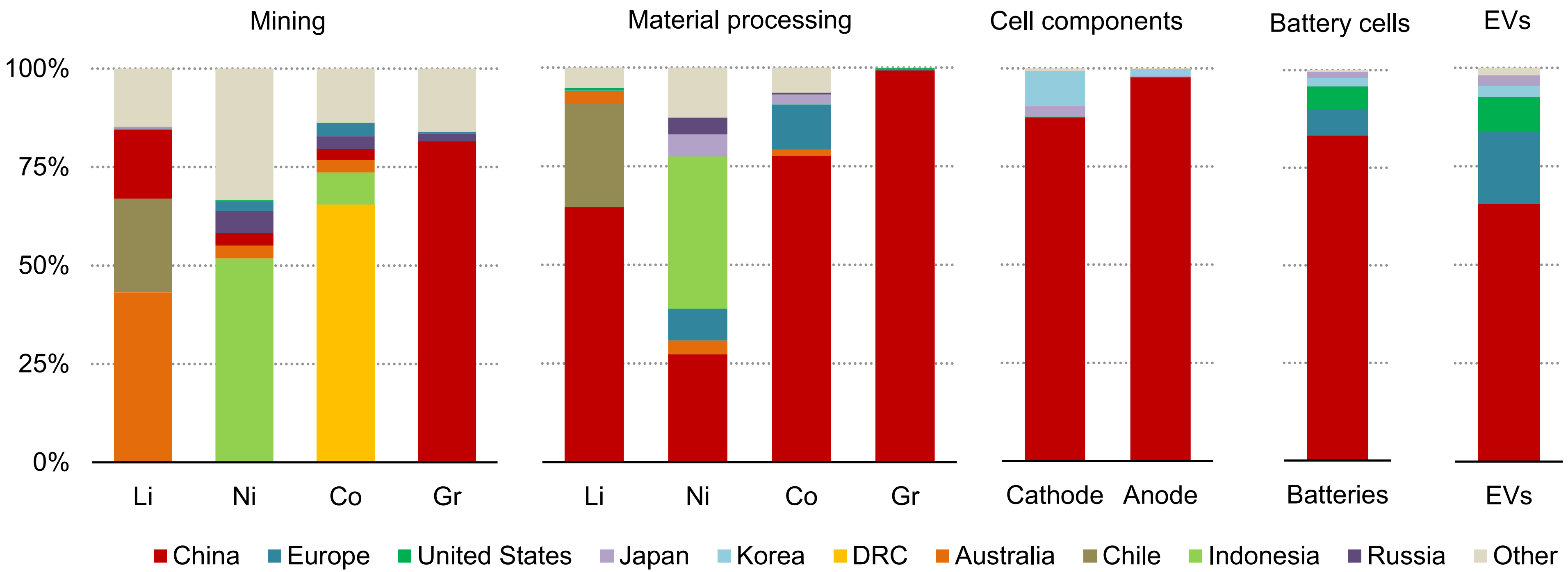
In terms of the anode, silicon-doped graphite anodes are increasing in market share with almost a third of electric car anode capacity market share. Higher fractions of silicon are also being used with 10% silicon graphite anodes doubling in market share in 2023 to 12%. Silicon doping increases the energy density of the graphite anode, and increased doping and higher quantities of silicon are expected in the near future.

Looking beyond lithium-ion chemistries, sodium-ion (Na-ion) batteries have experienced a surge of development in recent years, especially while lithium prices were high. As the name suggests, this chemistry contains no lithium and also requires less critical minerals than lithium-ion batteries. Leading batterymakers including CATL, Northvolt and many others announced their sodium-ion cells. However, the fall in lithium prices has diminished the advantage of sodium-ion chemistries and major ramping up plans have stalled or been delayed. The progress of sodium-ion batteries hinges on their price advantage over lithium-ion, with major influence of the lithium price.

All solid-state batteries (ASSBs) are the anticipated step-change technology for battery energy density and safety. There has been widespread industrial research and development in recent years, yet major technical challenges remain such as the typically high pressures required to ensure good electrode contact or relying on difficult-to-scale, expensive production processes. Progress has been made utilising hybrid solid-liquid electrolyte batteries, for instance from CATL and Quantumscape; however, the use of an organic liquid electrolyte diminishes any safety advantage and may even have higher risks than conventional lithium-ion batteries due to the use of lithium metal. Progress is also being made with ASSBs, with Samsung, an industry leader in solid-state, recently announcing plans for mass production in 2027. CATL also expects to produce small-scale production in the same year. Though ASSBs hold potential in the future, they are not expected to have significant impact until after 2030.

China dominates the downstream and midstream global EV battery supply chain

Geographical distribution of the global EV battery supply chain, 2023



Notes: Li = lithium; Ni = nickel; Co = cobalt; Gr = graphite; DRC = Democratic Republic of the Congo. Geographical breakdown refers to the country where the production occurs. Mining is based on production data. Material processing is based on refining production data. Cell component production is based on cathode and anode material production capacity data. Battery cells are based on battery cell production capacity data. EVs is based on electric cars production data. For all minerals mining and refining shows total production not only that used in EVs. Graphite refining refers to spherical graphite production only.

Sources: IEA analysis based on EV Volumes; Benchmark Mineral Intelligence; BloombergNEF.

Growth in China's manufacturing capacity has strong implications for EV battery supply chains

One of the most critical considerations in the global battery outlook is the strength of manufacturing capacity in China. China dominates the downstream battery supply chain, including processing of the battery minerals, cathode and anode material production, and battery cell and EV production. China holds 85% of battery cell production capacity and 90% of cathode and 98% of anode material production capacity globally. Over half of global processing for lithium and cobalt occurs in China. The country dominates the entire graphite anode supply chain end-to-end. China also produces two-thirds of the world's EVs. In almost all stages of the midstream and downstream supply chain, China has increased its market share since 2021.

China has been building battery plants and cathode and anode production capacity at a speed that exceeds projected demand. In 2023 China's maximum cell production capacity was more than double the amount needed to meet the country's battery cell demand. For cathode active materials, the manufacturing capacity anticipated in 2030 is about two times greater than the projected battery cell manufacturing capacity in the same year. In the case of anode active materials, this ratio increases to five times greater, raising doubts about whether all cathode and anode material manufacturers will be able to remain competitive in the face of such a surplus. There are several reasons for China's strong manufacturing position. The fruits of China's industrial strategy have been seen already in many sectors including solar, aluminium and steel. Years of government support, alongside a large and growing domestic market, have meant that the EV and battery industries in China have thrived and gained global market share. This has now set the stage for considerable price competition and consolidation. High-technology manufacturing is now a pivotal element of China's strategy for growth.

Ample manufacturing capacity across the battery supply chain is a double-edged sword. If excess production is pushed on to export markets, battery prices and EV prices may fall, which may be good for consumers and thus support progress towards climate goals. However, it could make difficult for producers globally to compete, increasing the level of supply concentration and exposing the supply chains to various physical and geopolitical risks.

For manufacturers in China in the coming years, the primary challenge will be to identify a sufficiently large export market to absorb their output and to improve low margins. Conversely, there is strong pressure on manufacturers in other regions such as the European Union and the United States to improve their cost competitiveness. The quality, cost and characteristics of cells and components provided by various suppliers, alongside local regulatory requirements and environmental, social and governance standards, will be crucial in determining how these markets develop.

The battery storage market is continuing its upward march

The battery storage market continued its remarkable growth in 2023, with installed capacity reaching over 85 GW. Almost half of this capacity, over 40 GW, was added in 2023 alone, another record year that saw additions doubling from 2022. A large part of the capacity growth has come from utility-scale systems, with behind-the-metre (BTM) battery storage responsible for about 35% of the annual additions on average. The strong increase in capacity additions over the last few years has been driven almost entirely by China, the European Union and the United States, which collectively accounted for nearly 90% of the capacity added in 2023.

The past two years have seen China rise above the United States to become the leading market for battery storage, with its share in annual global additions rising from around 20% in 2019 to 55% in 2023. In China, about two-thirds of the additional capacity was utility-scale, driven mainly by province-level mandates that encourage the pairing of new solar PV or wind projects with energy storage. BTM storage capacity grew strongly as well, with larger-scale commercial rather than residential users driving the uptake, underpinned by subsidies and a rising proliferation of time-of-use electricity tariffs.

The United States remains the second-largest battery storage market. Utility-scale projects accounted for nearly 90% of the additional capacity, with California, Texas and other states in the Southwest leading deployments. Falling costs have allowed batteries to make inroads into ancillary service markets and they are increasingly tapped to provide balancing services and secure capacity in states with high shares of variable renewables.

Installed battery storage capacity in the European Union grew 1.7 times in 2023, with annual additions rising to nearly 6 GW. Nearly 90% of the capacity growth was associated with BTM storage, mostly in Germany and Italy, where incentives such as tax breaks and low-interest loans, as well as high retail electricity prices support the pairing of rooftop solar with storage. In 2023, around 80% of the rooftop solar installed in Germany and Italy came with storage.

Capacity additions in Australia jumped to 1.3 GW in 2023, more than doubling last year's deployment levels, thanks in part to financial incentives that encourage the pairing of residential PV systems with batteries. Utility-scale battery storage capacity additions in Japan and Korea increased substantially in 2023, jumping to 400 MW in Japan and 300 MW in Korea. Chile, meanwhile, added nearly 250 MW of utility-scale storage in 2023, making it the first country in Latin America to deploy battery storage at scale.

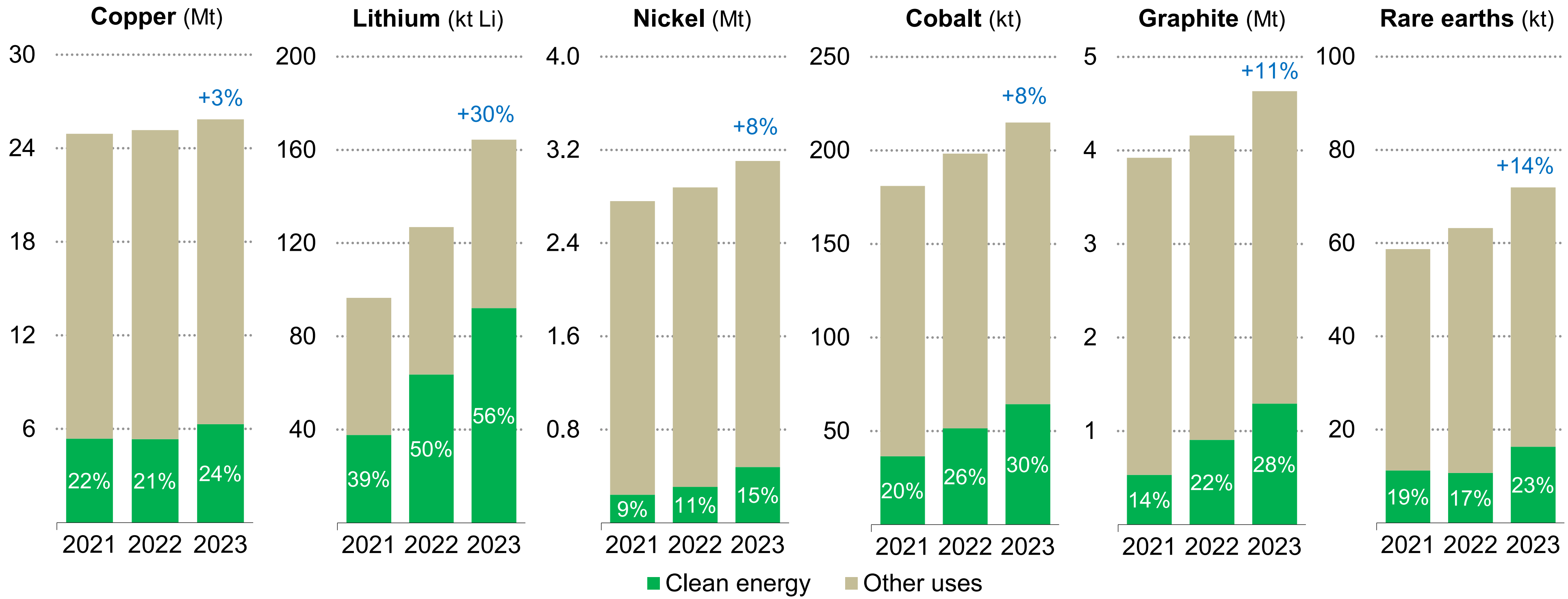
In other regions, capacity additions have so far been limited. However, in addition to further rapid acceleration in today's core markets, capacity growth is expected to broaden over the next few years. Energy storage targets and financial support mean that India in particular has significant potential to emerge as another large market for battery storage.

Lithium-ion batteries dominate the battery storage market today, accounting for more than 90% of the market. The chemistries available for lithium-ion batteries used in storage applications are the same as the ones available for the EV market. However, storage applications have different technical needs than EVs, and characteristics such as cost, capacity to charge/discharge frequently, and lifetime are prioritised over energy density. This has led to a shift towards LFP batteries, which accounted for about 80% of the total battery storage market in 2023, up from about 65% in 2022. The growing battery market, together with the resurgence of LFP batteries for EV applications, is leading non-Chinese battery manufacturers to develop their own LFP batteries, which today are almost exclusively produced in China. Lithium-ion battery technology is set to remain a key part of short-duration (eight hours or less) storage, but alternative technologies (such as vanadium flow batteries) are being developed either to compete or to complement it.

Market trends for critical minerals

Demand for key energy transition minerals continued to grow strongly in 2023, propelled by the expansion of clean energy technologies

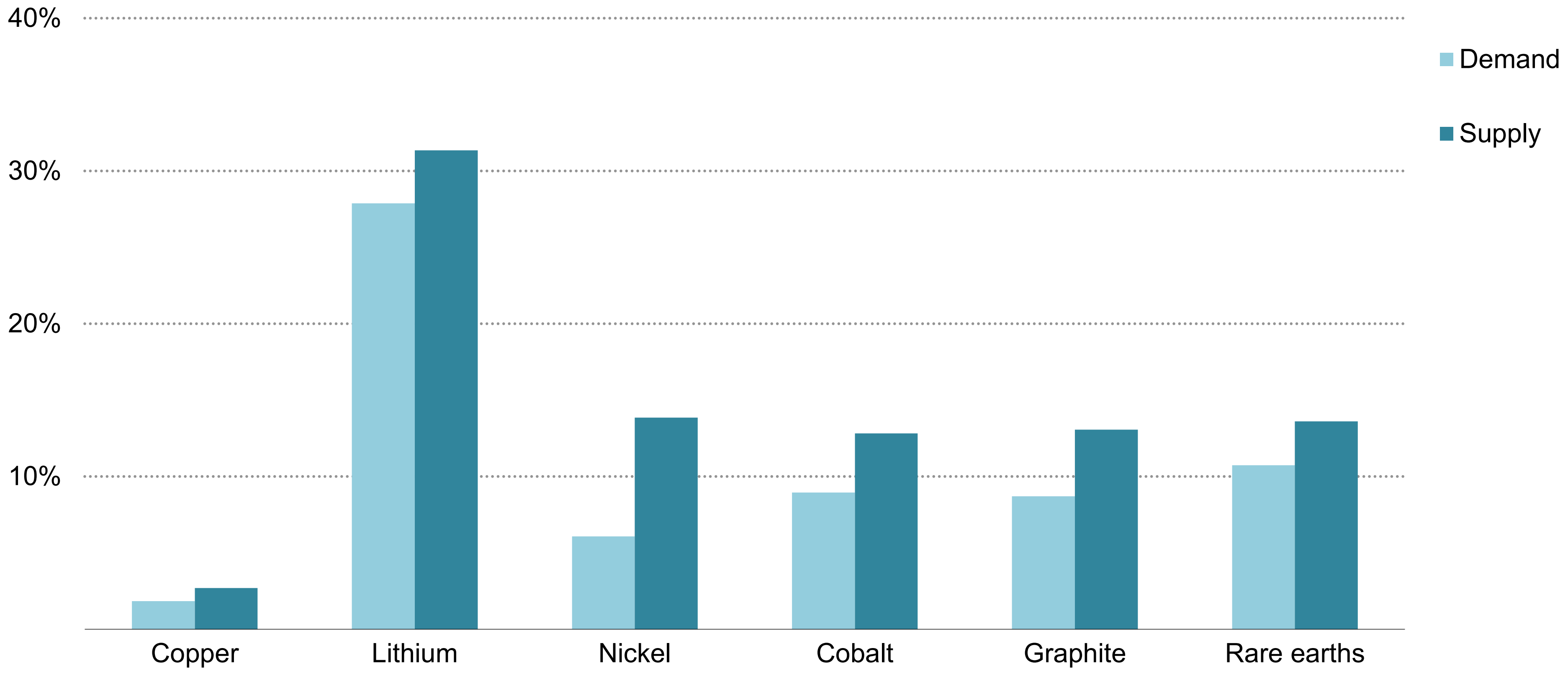
Demand outlook for selected minerals, 2021-2023



Notes: Rare earths include the four magnet elements: neodymium, praseodymium, dysprosium and terbium. Demand for clean energy applications includes consumption for low-emissions power generation, EV and battery storage, grid networks and hydrogen technologies.

However, supply has expanded at a faster rate than demand, resulting in downward pressure on prices

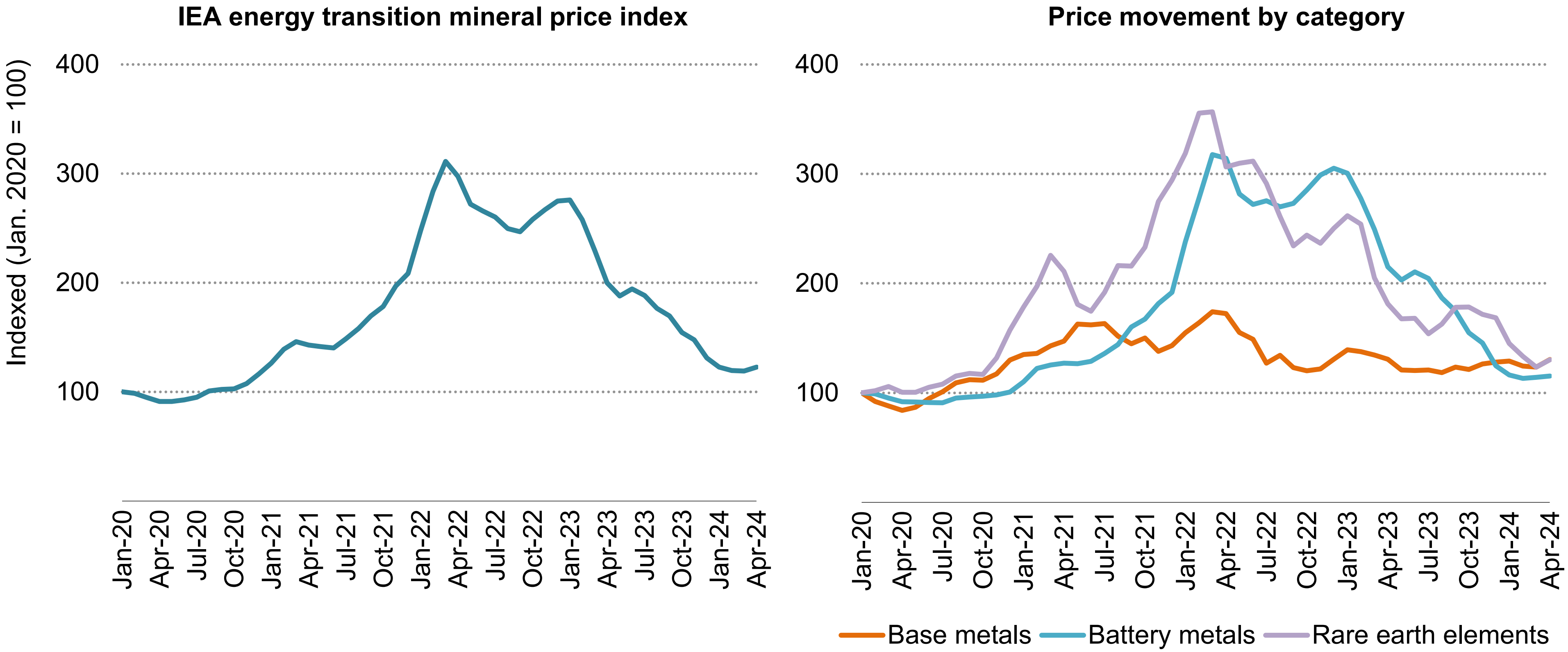
Annual average demand and supply growth rates between 2021 and 2023 for selected minerals



Notes: Supply growth rates are based on refined output. The figure for graphite includes both natural and synthetic graphite.

Prices for key minerals have returned to pre-pandemic levels

Mineral price developments

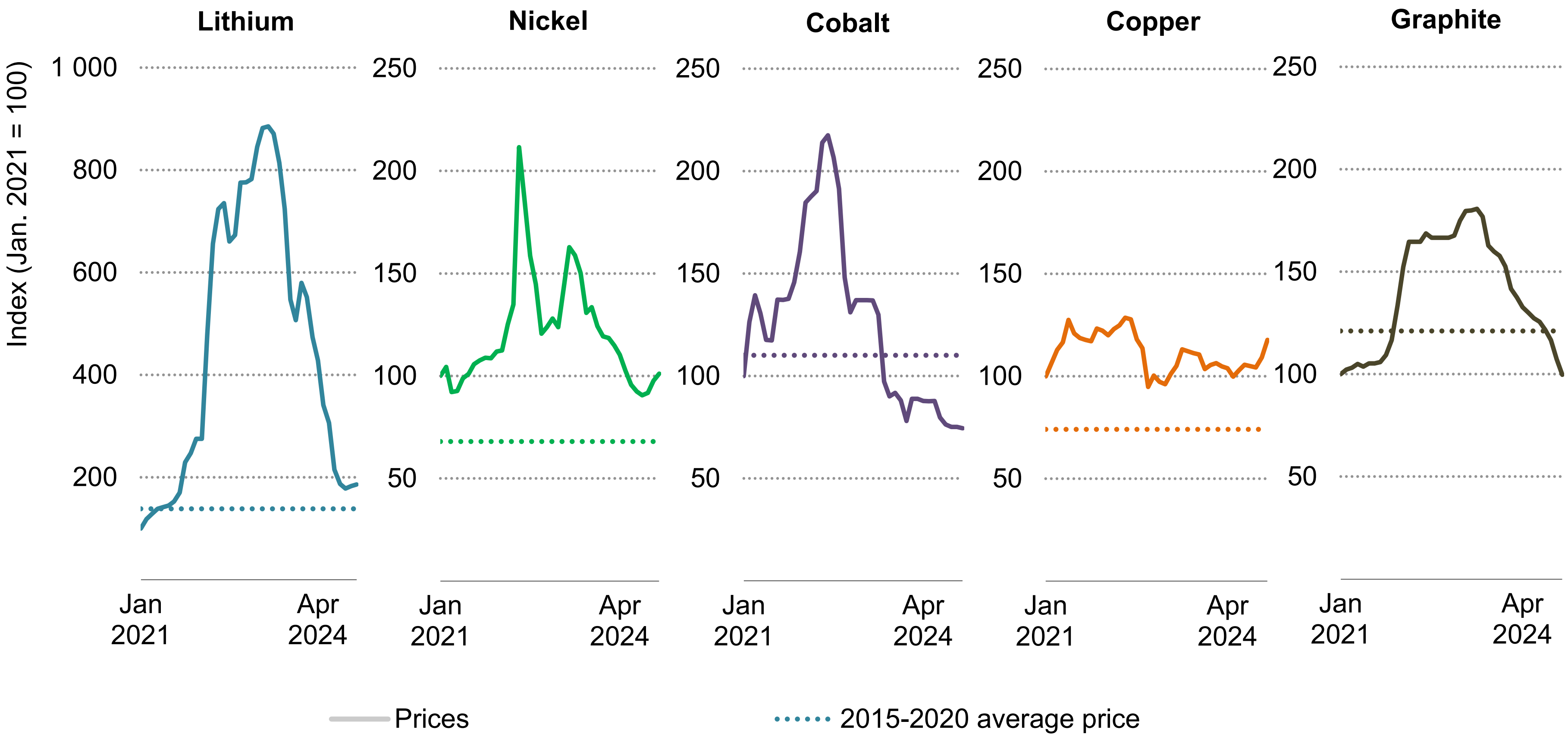


Notes: IEA Energy Transition Minerals price index is a basket price of copper, lithium, nickel, cobalt, graphite, manganese and neodymium. On the right-hand chart, base metals include iron, aluminium, zinc and copper. Battery metals include lithium, nickel, cobalt, graphite and manganese. Rare earth elements include neodymium, praseodymium, dysprosium and terbium.

Sources: IEA analysis based on Bloomberg and S&P Global.

Battery critical minerals have seen the greatest volatility

Critical minerals prices, 2021-2024

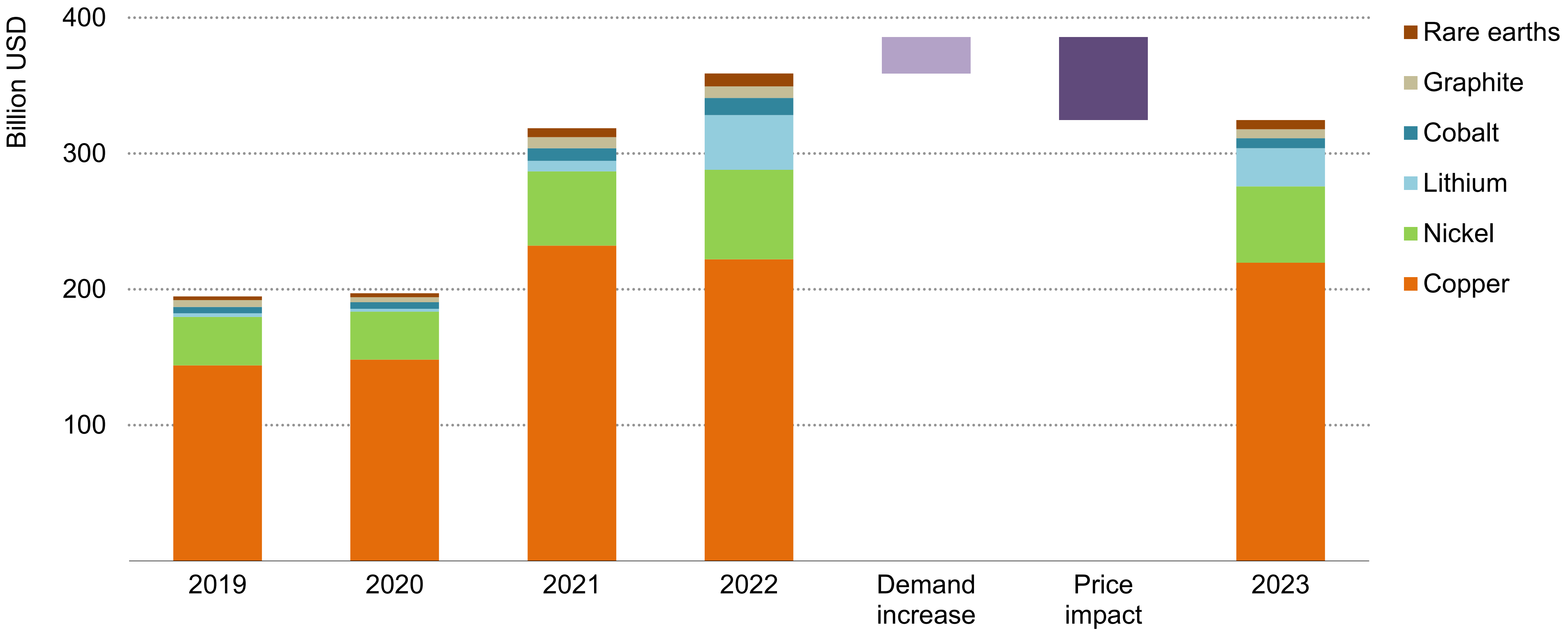


Notes: Graphite historical average from 2016-2020. Assessment based on the London Metal Exchange (LME) Lithium Carbonate Global Average, LME Nickel Cash, LME Cobalt Cash and LME Copper Grade A Cash prices and China flake graphite – 194 free on board. Nominal prices.

Source: IEA analysis based on S&P Global and Bloomberg.

Due to falling prices, the market size for key energy transition minerals contracted by 10% to USD 325 billion in 2023, despite demand growth

Market size for key energy transition minerals, 2019-2023



Notes: The market size for rare earth elements is based on the aggregate size of four magnet materials. In this year's assessment, rare earth elements and refined copper based on secondary scrap were included in the calculation, which raised the 2022 market size to USD 360 billion (up from USD 320 billion in the Critical Minerals Market Review 2023).

The widespread decline in critical mineral prices in 2023

The critical minerals market had a turbulent year in 2023 and the main story of the year was falling prices. Battery minerals saw particularly large declines with lithium spot prices plummeting by 75% and other key materials such as nickel, cobalt, manganese, and graphite seeing declines of 30-45%. The IEA Energy Transition Mineral Price Index, which tracks a basket price of copper, major battery metals and rare earth elements, tripled in just two years starting in January 2020, but it began to slide from the beginning of 2023, returning to pre-pandemic levels. However, except for cobalt and graphite, prices remain higher than the historical averages observed in the 2010s. In contrast, prices for copper stayed relatively resilient. While expectations for a strong post-pandemic demand recovery did not materialise at scale, actual output fell short of anticipated supply, leading to tighter market conditions, particularly for copper concentrates.

Several factors contributed to the drop in prices. The slowing growth rate of EV battery sales, coupled with large-scale cell and cathode production, has led to a substantial accumulation of downstream products in inventory. China's expansion of battery plants, as well as cathode and anode production capacity, has far outpaced demand. This expansion has been a key driver behind the considerable build-up of inventory throughout the supply chain, resulting in reduced purchases of new materials. Furthermore, amid record high prices in 2022, many downstream consumers also made efforts to secure ample volumes to ensure business continuity.

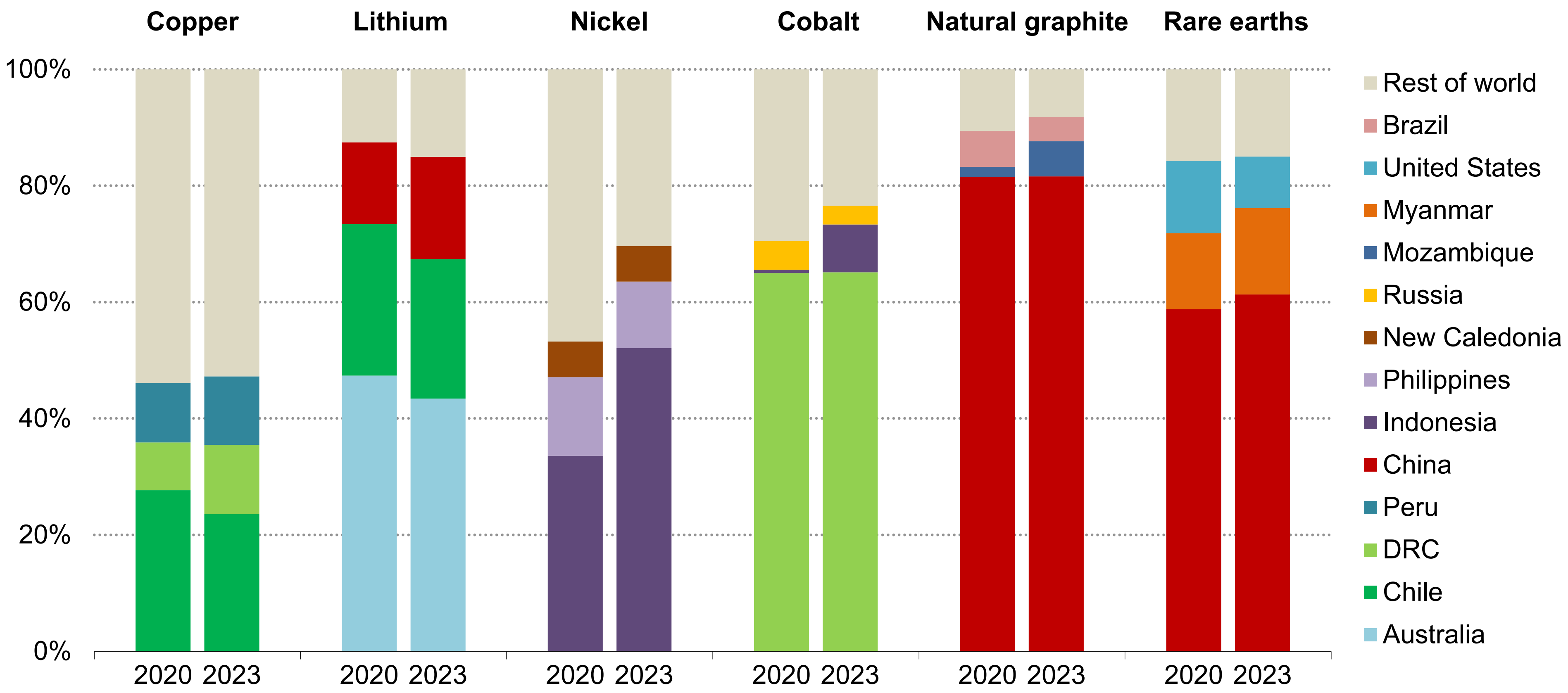
The rate of demand growth remained robust in 2023, with lithium demand rising by 30% and demand for nickel, cobalt, graphite and rare earths expanding by 8-15%. Clean energy applications were one of the primary contributors to this demand growth. Across all key minerals, the share of clean energy technologies has risen consistently. EVs cemented their position as the largest-consuming segment for lithium, and increased their share considerably in the demand for nickel, cobalt and graphite.

Nonetheless, the ramp-up of new supply outpaced demand growth in the past two years. From Africa to Indonesia, and to China, new projects came online relatively quickly, adding sizeable volumes to the supply pool. The remarkable increase in nickel supply from Indonesia is a notable example.

Overall, a combination of demand and supply-side trends, alongside a correction of overly steep price rises in 2021-22 contributed to the lower price environment, which is likely to continue in 2024. As a result, despite demand growth, the market size for energy transition minerals contracted by 10% to USD 325 billion in 2023. It would have been 20% higher if prices had remained at 2022 levels.

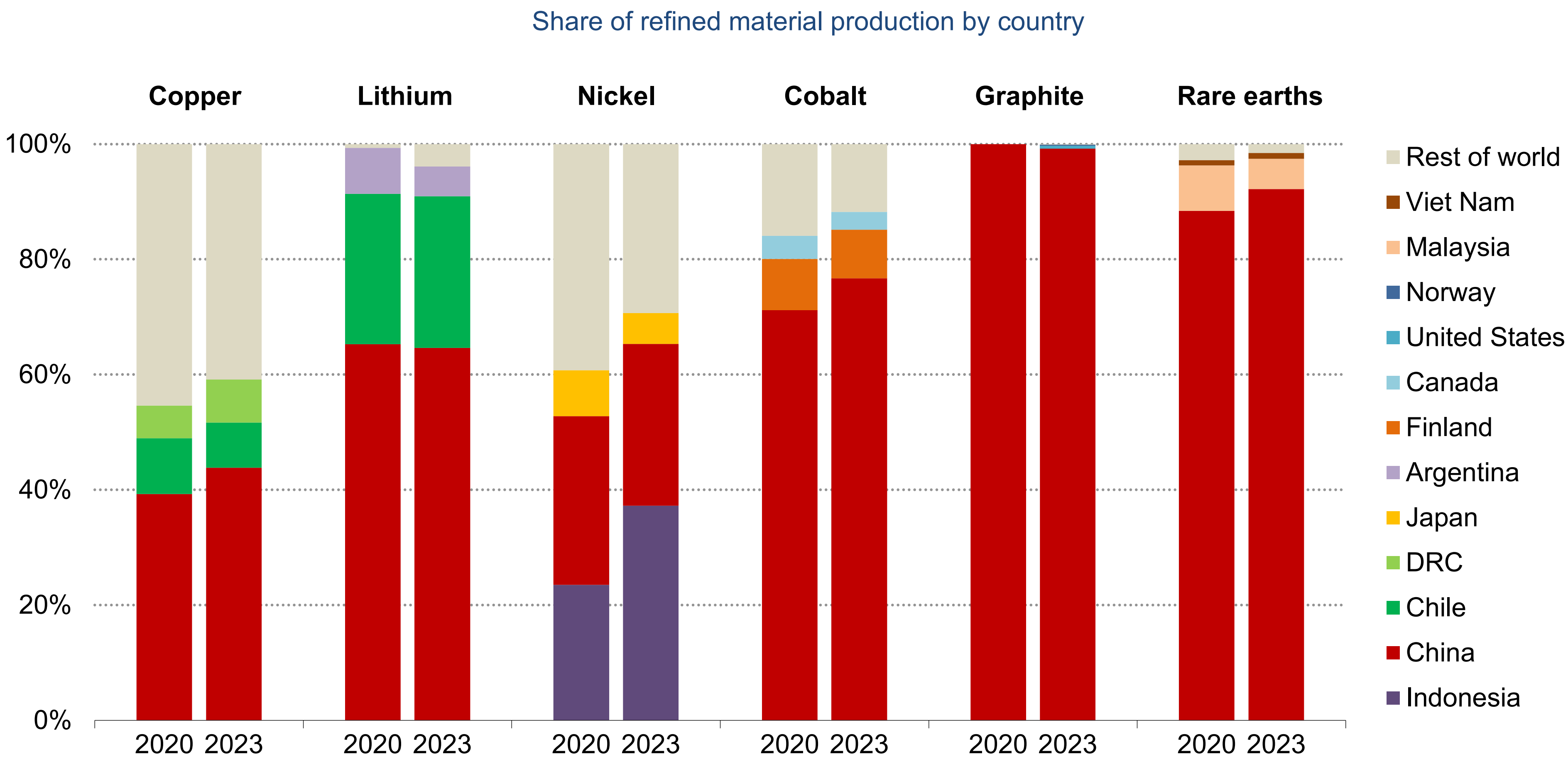
Production growth has been accompanied by rising levels of geographical concentration, with the trends particularly pronounced for nickel and cobalt

Share of mined or raw material production by country



Notes: DRC = Democratic Republic of the Congo. Graphite extraction is for natural flake graphite. Rare earths are magnet rare earths only.

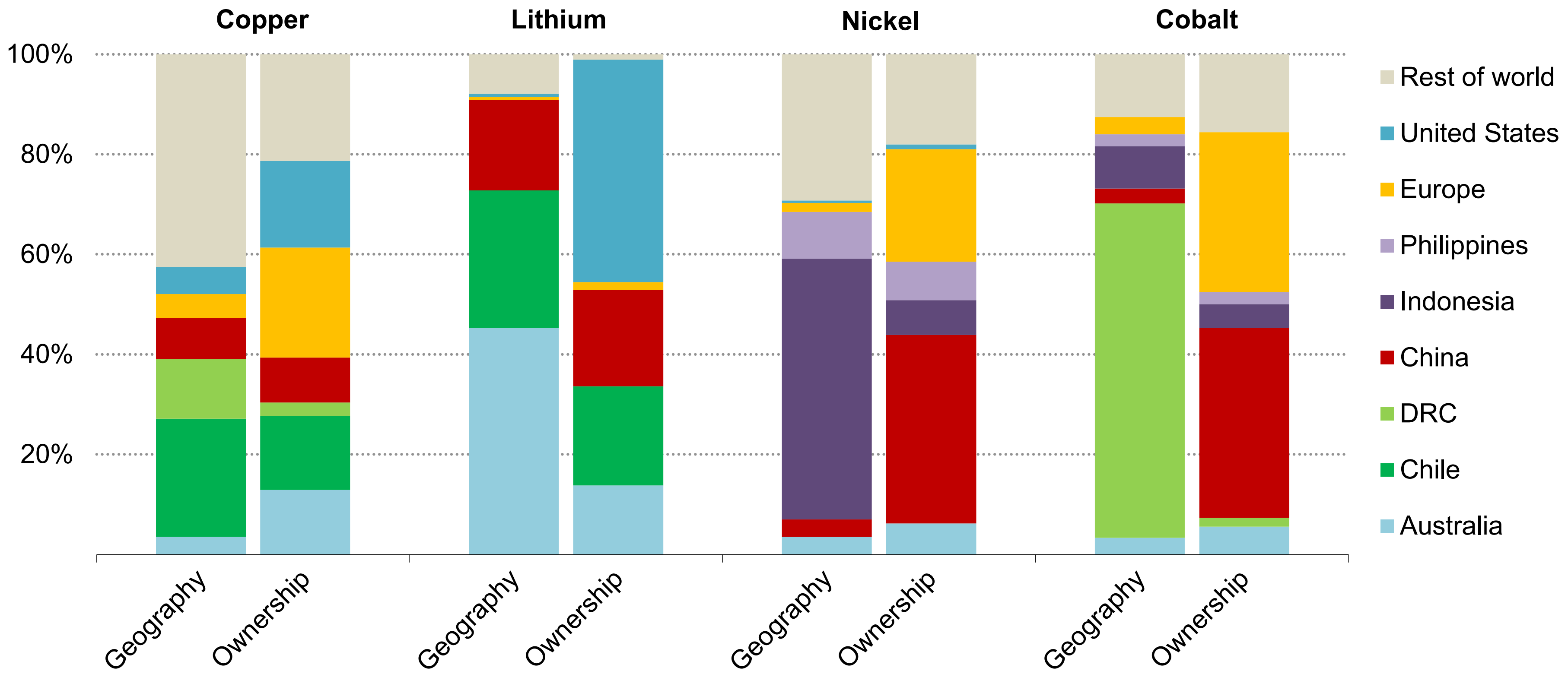
The level of geographical concentration for refined products has increased in recent years



Note: Graphite is based on spherical graphite for battery grade. Rare earths are magnet rare earths only.

Mining concentration looks different if viewed through the lens of asset ownership, with US and European companies playing a greater role

Mining concentration by geography and ownership



Notes: Ownership based on company headquarters location. For projects run by multiple companies, production is assigned to the company with the largest share. For copper, data are on the top 20 mining companies in 2023 representing 57% of production. For lithium, data cover 100% of production in 2023; for nickel, 93% of production; and for cobalt 97% of production.

Sources: IEA analysis based on S&P Global and Wood Mackenzie.

New and more diversified supply sources remain vital, especially for refined materials

Production of key energy transition minerals has expanded substantially over the past several years, easing concerns about near-term supply shortages. However, as underscored already in the IEA's first Critical Minerals Market Review in 2023, this growth has come with increasing levels of geographical concentration. While high levels of supply concentration are well-known in the critical mineral space, the issue has been exacerbated by further production increases from today's dominant suppliers.

In the case of refined materials, the share of the top three producing nations have all increased since 2020, except for lithium. This trend is most pronounced for nickel and cobalt, where the rise of Indonesia has significantly boosted the level of supply concentration. Between 2020 and 2023, Indonesia's share of mined nickel production increased from 34% to 52% and its share of refined nickel increased from 23% to 37%. Meanwhile, 2023 also witnessed a proliferation of trade restriction measures, including increased Chinese controls over exports of gallium, germanium, graphite and technologies for processing rare earth elements.

For mining, however, assessing production by ownership (based on the leading owner company's headquarter location) shows a very different picture compared with the geographical mine location. Companies in the United States and Europe play a much greater role in the supply of all critical minerals than what the geographical location of mines may suggest. Much of this is from some of the largest multi-national mining majors such as Glencore and Rio Tinto.

Although the majority of copper production occurs in Chile, European companies are the leading copper producers with over 10% of production, with Glencore, Rio Tinto and Anglo American playing major roles, and US companies controlling the second-largest amount of production. For lithium, Australia and Chile are the primary locations of raw material production, whereas US companies such as Abermarle are a major shareholder of over 40% of producing mines.

Both nickel and cobalt also show stark differences between the geographical location of mines compared with the ownership. Although Indonesia is the leading location of nickel mining, Indonesian companies hold less than 10% of production. Chinese companies are the major nickel mine owners, accounting for around 40% of production. European companies also have a sizeable share with over 20% of supply, predominantly due to operations in Indonesia owned by Eramet. For cobalt, the majority of mines are located in the Democratic Republic of the Congo (DRC), whereas European companies such as Glencore and Chinese companies such as CMOC own a third each of the supply. Notably, DRC-owned companies account for less than 5% of production.

Short-term market developments for key energy transition minerals

Short-term market developments for key energy transition minerals

Copper

Demand for refined copper increased by 2.7% in 2023, up from 0.9% in 2022, almost entirely driven by growing consumption in China and India. Demand in other regions registered a modest decline. The growth in China was predominantly underpinned by copper uses in construction and electricity networks, a trend expected to persist in the coming years. Indications from China's 'Two Sessions' meeting in March 2024 signal a continued emphasis on expanding copper usage, particularly in renewable energy and grid expansion.

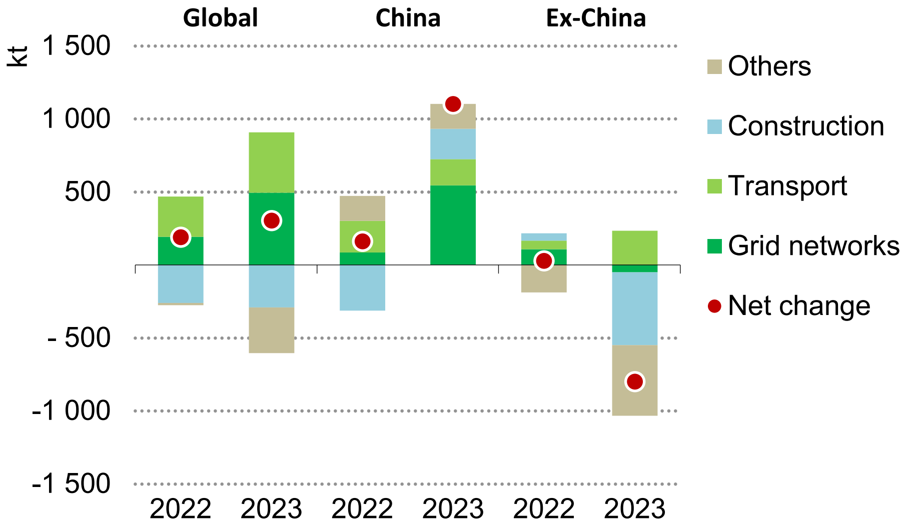
Mined copper output saw an increase of less than 2% in 2023, with notable growth in the Democratic Republic of the Congo (DRC) and Peru offset by declines in Chile and elsewhere. Refined copper supply expanded by 4% in 2023, primarily driven by increased production in China, with some contributions from the DRC.

In early 2024, copper prices saw a strong increase as lower-than-anticipated mined output tipped the concentrate market balance toward a slight deficit, contrary to earlier expectations of surpluses. The closure of the Cobre Panama mine and downgraded production guidance by Anglo American, Vale and Southern Copper contributed to this result. Several supply disruptions are continuing in 2024, for example, production at the Radomiro Tomic mine in Chile was halted due to a worker strike in March. As many smelters sought to secure copper concentrates, the spot treatment and refining charges (TC/RC) plummeted by 80% between October 2023 and February 2024. In response, Chinese smelters agreed on several measures to limit the decline in TC/RCs, including replacing concentrate usage with scrap, bringing forward the schedule for maintenance, reducing utilisation rates for unprofitable facilities and postponing new projects.

The tightness in the concentrate markets extended to the scrap market as many smelters sought to increase their usage of scrap to complement concentrates. Over recent months, there has been a noticeable uptick in China's scrap imports, with repercussions in the global scrap market.

Limited growth in mined supply is anticipated for 2024. However, in 2025 and 2026, several new projects and expansion plans are expected to ramp up, such as Tenke Fungurume (DRC), Quebrada Blanca Phase 2 (Chile) and Udokan (Russia). These would bring additional volumes to the market but risks remain if these projects fail to meet expected growth targets or experience slower ramp-ups. Possible sanctions on Russian copper may not materially affect the market as many European companies have already diversified their supplies and a large portion of Russian volumes currently flow to China and Türkiye.

Year-on-year change in copper consumption by sector and by region, 2022-2023



Note: Includes direct use of scrap.

Lithium

In 2023, lithium demand rose by around 30%, maintaining the level of growth seen in 2022. Raw material supply increased by 30% with traditional producers such as Australia and Chile being joined by new players such as Argentina and Zimbabwe. Lithium chemical production experienced even greater expansion by 40%, primarily driven by China.

Lithium was a notable beneficiary during the price rally in 2021 and early 2022, but in 2023 it was the commodity that was most affected by price downturns. The substantial build-up of inventories in the downstream battery value chain (e.g. battery cells, cathodes) progressively dampened purchasing activity in 2023. Meanwhile new supplies from Australia, Argentina and China continued to increase throughout the year, further pressuring prices. Lithium prices fell by over 75% during the course of 2023, returning to pre-pandemic levels. This steep decline prompted various actions by producers to reduce output and scale back expansion plans. Core Lithium decided to suspend mining operations at its Finniss mine to focus on processing stockpiled ore. Albemarle outlined plans to reduce capital expenditures for 2024 while implementing cost-cutting measures. Talison announced a production reduction plan in response to market conditions.

Lithium prices saw a slight uptick in March-April 2024, supported by production cuts and expectations for the end of the destocking cycle. The revival of downstream activities may provide some upside for prices. However, a significant price surge in the near term is difficult to envision. Several potential supply sources stand ready to ramp up production, which could cap the potential for a substantial price increase. For example, it is estimated that lepidolite assets in China currently runs at 40% utilisation rates but could return to the market if prices were to rise substantially in the short term. Additionally, spodumene assets in China, Canada, Brazil and Africa are also positioned for robust growth. On the chemical front, numerous lithium refineries are scheduled to commence operations and expand capacity in 2024 and 2025, primarily in Argentina, Australia and

China. Most of the recently announced supply reductions or postponements have been associated with hard rock lithium, not chemicals.

While investment and exploration activities in the lithium sector remained strong in 2023, the enduring low prices may dampen investment appetite for new greenfield projects, thereby impacting medium-to-long-term market balances.

Nickel

Nickel was another material that experienced significant price declines, with prices falling more than 40% in 2023. Several factors, including a downstream inventory overhang, the accelerated adoption of LFP chemistries, and subdued stainless steel demand, particularly in advanced economies, contributed to this downturn. However, the primary driver was oversupply, driven by a surge in output from Indonesia.

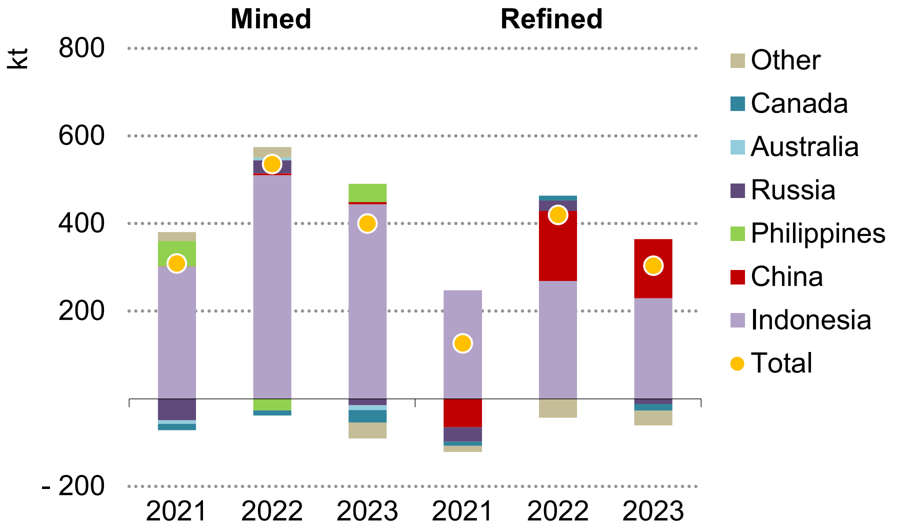
While demand for nickel grew by 4% in 2022 and 8% in 2023, mined nickel supply increased by 19% in 2022 and 9% in 2023. In 2023, Indonesia's production growth was greater than global output growth, implying reduced output from other producers. Refined nickel production expanded by 14% in 2022 and 2023 each, again led by Indonesia and China.

The delivery of high-pressure acid leaching (HPAL) projects in Indonesia, aimed at producing high-purity nickel products from laterite resources, exceeded initial projections in terms of speed. Indonesia's HPAL projects yielded 180 kt of nickel in 2023, a significant rise from 88 kt in 2022. The development of a process to convert nickel pig iron (NPI) to nickel matte further contributed to notable output growth in the country.

In recent years, the proliferation of methods to convert low-purity Class II products and intermediates has blurred the traditional boundary between Class I and Class II products, contributing to a decline in nickel prices on the London Metal Exchange (LME) where high-purity Class I products are traded. With the notable discounts of nickel sulphate and NPI to the LME price, several producers in China (and Tsingshan in Indonesia) have begun producing higher-grade nickel cathodes suitable for delivery on both the LME and Shanghai Future Exchange (SHFE). In July 2023, Huayou's nickel products were accepted by the LME, and other nickel sulphate producers such as China's GEM and CNGR are following suit. Overall, the oversupply of Class II and intermediates in Indonesia and China and mechanisms to bring the surplus of Class II products to the Class I market coincided with weak demand, causing a sharp correction in prices.

These market conditions have taken a heavy toll on many higher-cost producers, prompting them to temporarily suspend production or, in some cases, cease operations. Panoramic Resources made the decision to halt operations at its Savannah nickel mine in West Australia. BHP is reassessing its Nickel West operations and planned investments for the West Musgrave project in Australia. This has sparked discussions about price premiums for nickel products with high environmental and social performance. However, there are limited indications thus far that consumers favour products with lower environmental and social impacts (see the nickel section in Chapter 2).

Change in nickel supply by country, 2021-2023



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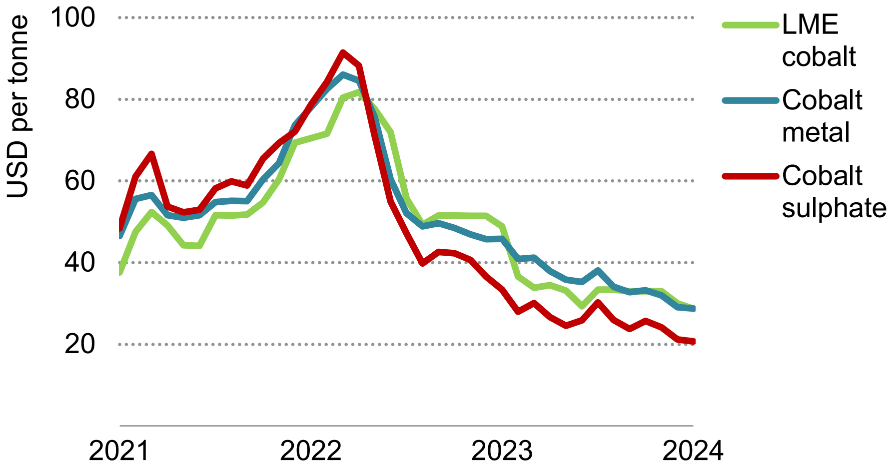
In 2023, the nickel market saw a surplus equivalent to around 8% of annual consumption. While the magnitude of this surplus may diminish in 2024 due to growing demand and production cuts, prices could remain suppressed given the numerous projects in the pipeline, particularly those slated to come online in Indonesia in 2024 and beyond. Indonesia's share of global nickel supply has risen significantly, climbing from 34% in 2020 to 52% in 2023 for mined output and from 23% in 2020 to 37% in 2023 for refined output. The persistent low-price environment may further bolster this share in the years ahead.

Cobalt

Cobalt prices remained subdued throughout 2023 due to a combination of production growth from the DRC and Indonesia coinciding with weak demand. Over the past two years, demand for cobalt has increased by 8-10% annually, while mined cobalt supply expanded by an average of 16% and refined cobalt supply by 13%. In 2023, prices for cobalt metal performed better than those for cobalt sulphate, signalling weaker demand in the battery sector compared with demand for alloys and magnets.

The DRC, the largest supplier with a 65% market share, delivered the largest increase in production in 2023. The ramp-up of CMOC's Kisanfu mine in the DRC exceeded expectations from the industry, and the resolution of the dispute between DRC's state-owned mining company Gécamines and China's CMOC allowed the Tenke Fungurume mine to resume exports. Consequently, CMOC surpassed Glencore as the largest supplier of mined cobalt to the global market. Indonesia rapidly ascended to become the second-largest producer, driven by the burgeoning production of mixed-hydroxide precipitate (MHP) from its HPAL facilities. For refined cobalt, China has dominated production volume growth over the past few years, with virtually no growth observed in other regions.

Price developments for cobalt, 2021-2024



Notes: Cobalt metal is based on China Cobalt Metal 99.8%. Cobalt sulphate is based on Cobalt sulphate 20.5% China. Quality adjusted.
Sources: IEA analysis based on S&P Global and Bloomberg.

Subdued prices prompted many producers to stockpile cobalt hydroxide or metal in an effort to bolster future profitability, though the effectiveness of these measures hinges on the evolution of near-term market balances. Cobalt prices are expected to remain subdued in 2024 as supply growth continues to outpace demand growth. While overall battery deployment continues to increase, the trend in battery chemistry choices is shifting towards those using less cobalt. Although the pace of supply growth is anticipated to slow in 2024, significant price support in the near term is unlikely, although logistical bottlenecks or unexpected supply disruptions of large mines could trigger a brief price rally.

Graphite

In 2023, graphite consumption grew by 11% to 4.6 Mt, with battery-related demand growing by 40% to 1.5 Mt. Mining production of natural graphite has been stable, while synthetic production continued to ramp up, allowing total graphite supply to grow by 10.5% and reach 5.5 Mt.

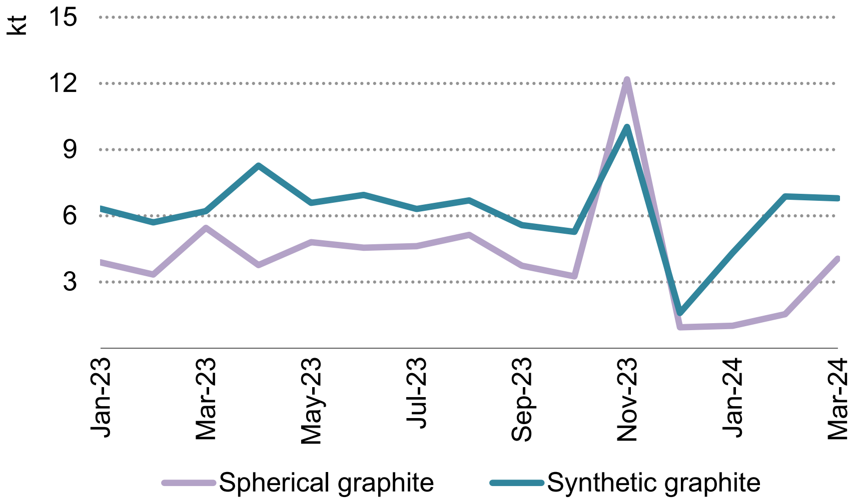
Production is ramping up in more diversified areas, such as the Lac-des-Îles mine coming back online in Quebec, and production starting in Madagscar's Molo mine. New developments are taking place with more integrated models, with anode producers building increasingly intregrated supply chains – such as Korea's POSCO securing supply of 24 kt per year from the Balama mine in Mozambique, whose owner is also developing anode material production in Louisiana.

As for other key battery metals, graphite prices experienced a significant drop in prices over the course of 2023 with prices for natural flake graphite falling by 30% and spherical graphite by 45%.

One of the most significant developments for graphite this year is that since December 2023, natural and refined battery-grade graphite are subject to export controls from China. These are not the first set of Chinese export controls for critical minerals, with restrictive measures taken for rare earth elements in the early 2010s and for gallium and germanium since July 2023, but it is the first time these happened for a critical input of the EV supply chain. In January and February 2024, exports to Japan and Korea – key EV anode producers outside of

China – were significantly below average although they returned to normal levels in March. In parallel, new US IRA guidance is creating incentives for a number of battery manufacturers to source graphite from outside of China. While the market is well supplied for the moment, this raises an important question about the availability of graphite that is compliant with a range of policy measures aimed at promoting supply chain diversification. It remains to be seen whether market fragmentation creates divergent regional price dynamics going forward.

China's exports of graphite



Source: IEA analysis based on Wood Mackenzie.

Rare earth elements

The rare earth elements (REE) industry is still bearing the legacy of concerns around risk and volatility which emerged during the 2010-2011 price spike. Over several decades, China has built its position in the REE market with the long-term goal of growing its downstream industry and has become the leader in refined rare earth technologies (see the rare earth elements section in Chapter 2). The REE market is fundamentally driven by developments in China, which is the single-largest source of mined rare earths from two principal areas. The largest source of light rare earths (LREE) - including neodymium and praseodymium, is a by-product supply from the Bayan Obo iron mine in Inner Mongolia. But China also hosts vast quantities of heavy rare earths (HREE) - including dysprosium and terbium, in ionic adsorption clay deposits in southern China. With additional mine supply spread across the country, China is the largest producer of mined REEs.

The supply chain for REEs and permanent magnets is complex, regionally concentrated and marked by a lack of transparent pricing. In 2023, the REE markets saw an oversupply from China and a lower-than-expected downstream demand. Chinese production quotas for LREEs increased modestly in the second half of 2023, raising the availability of materials in the market. Neodymium prices are estimated to have fallen by 45% over the course of 2023. Net profit for the China Northern Rare Earth Group, one of the largest global producers, was estimated to be in the range of CNY 2.17 billion (Yuan renminbi) (USD 303 million) to CNY 2.33 billion in 2023, a decline of around 60% from CNY 5.98 billion (USD 934 million) in 2022.

As China imports HREE feedstock from Myanmar and Laos for domestic processing, Myanmar's decision to close its borders raised concerns about the reliable supply of HREEs. However, the latest data indicates that the closures had little impact on trade flows. REE mining activity mainly occurs in Kachin state, which has significant autonomy. Meanwhile, there was an increasing volume of HREE feedstock from Lao PDR to China, which also contributed to alleviating concerns about material availability.

While the markets appear to be well-supplied to meet near-term demand, the current low-price environments could delay projects planned outside China, further pushing back already lengthy lead time projects intended to boost diversification. Another area of concern could be tightened supply of HREEs in the medium term. While a lot of attention was paid in the last decade to LREEs used in EV motor magnets (neodymium and praseodymium), HREEs such as dysprosium and terbium are also key components, but their relative supply from the main rare earth deposits is not in sync with their use. Avoiding this would require all currently announced projects to secure funding and scale up rapidly.

Concerns surrounding transparent reporting in rare earth markets also need to be addressed to avoid situations such as the recent legal action against major players in Viet Nam, which could put expected supplies at risk or create barriers for diversification.

Will uranium be a bottleneck for a nuclear comeback?

After a decade of slow deployment, a changing policy landscape is creating opportunities for a nuclear comeback. Nuclear power capacity increases from 420 GW in 2023 to 500 GW by 2030 and 770 GW by 2050 in the Announced Pledges Scenario (APS), with growth mainly in China and other developing economies, while advanced economies carry out lifetime extensions and look to builld new projects to offset retirements. Large-scale reactors remain the dominant form, but growing interest in small modular reactors increases the potential for nuclear power in the long run.

After climbing steadily for a couple of years, spot prices for uranium oxide spiked in the second half of 2023, reaching over USD 100 per pound in February 2024, the highest price seen in over 15 years, before falling again to just under USD 90 in March. Amid ongoing uncertainty over the possibility of import restrictions from the United States and European countries on supplies from Russia, news in 2023 of a coup in Niger and a sulphuric acid shortage in Kazakhstan put pressure on supplies of uranium oxides. While the current price spikes are not entirely supported by market fundamentals given that many countries have sizeable stockpiles for nuclear fuels and it will take many years for planned nuclear capacities to come online, the recent price rally highlights a growing concern around uranium supplies to support the growth of nuclear power.

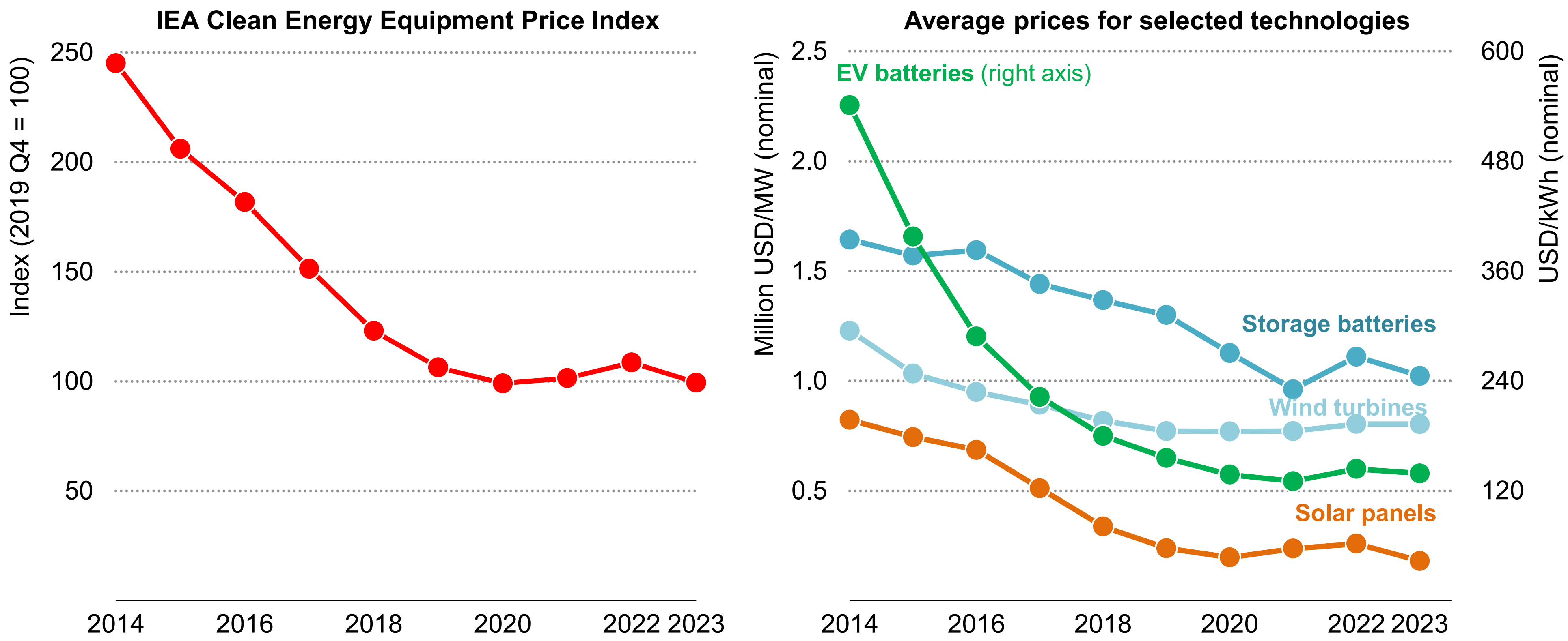
Following the invasion of Ukraine, Western governments have become increasingly concerned about Russia's role in the nuclear fuel supply chain. In recent years, Russia has accounted for a third of all conversion and 40% of enrichment services globally. Russia is also the only commercial supplier of high-assay low-enriched uranium (HALEU) necessary for certain advanced reactor designs.

Several governments have recently announced moves to reduce dependence on Russia. In January 2023, the US Department of Energy announced awards to the conversion industry to develop its strategic uranium reserve. In April 2023, Canada, France, Japan, the United Kingdom and the United States announced an agreement to support the stable supply of nuclear fuel and "undermine Russia's grip" on nuclear fuel supply chains. Since then, the United Kingdom and the United States have announced moves to encourage the development of HALEU enrichment capacity.

Nonetheless, it is too early to tell if high prices and supply supports seen in 2023 will be sufficient to encourage Western suppliers to expand production. US domestic production of uranium in 2023 remained at historically low levels. However, some producers in Canada and the United States have announced that they will restart production in 2024 at previously mothballed facilities.

Investment trends

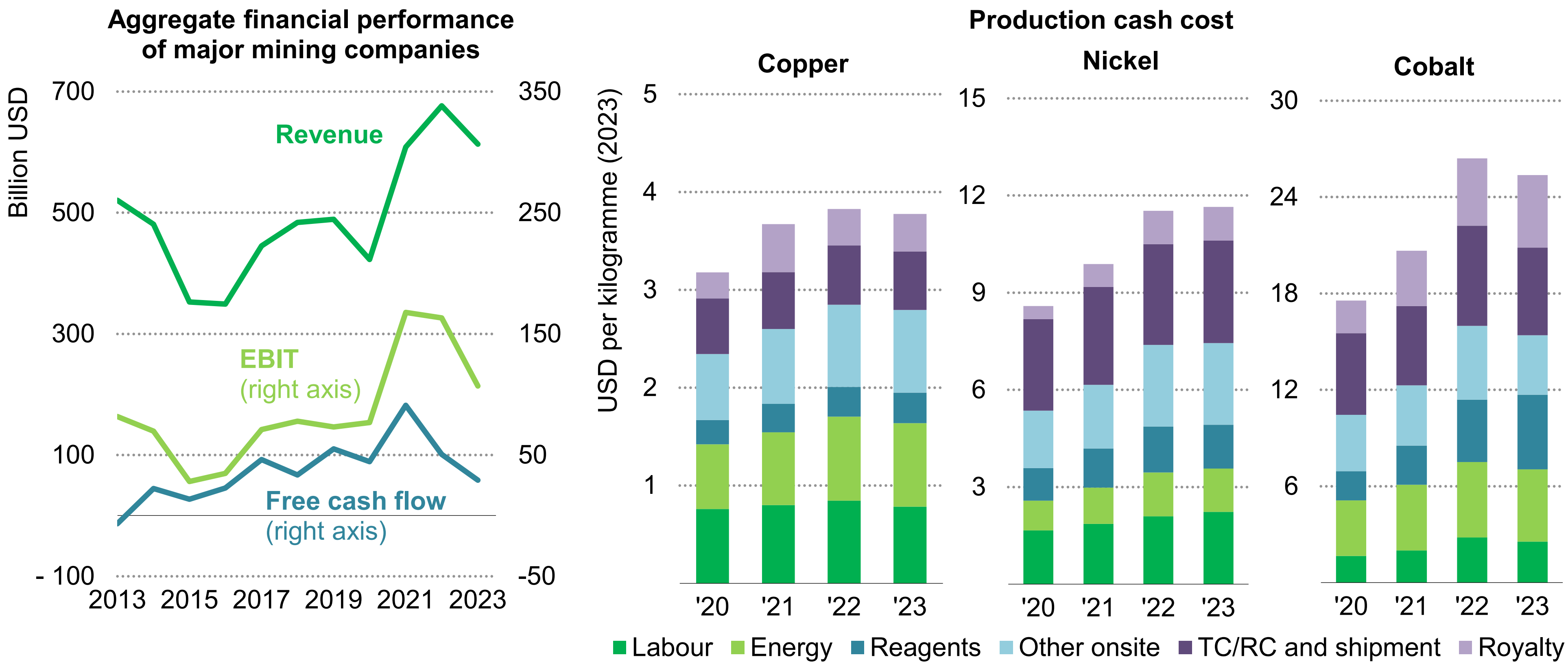
Reduced material prices and increased manufacturing capacity underpinned major cost reductions for clean energy technologies, with solar PV and batteries reaching record lows



Notes: The IEA Clean Energy Equipment Price Index tracks price movements of a fixed basket of solar PV panels, wind turbines and lithium-ion batteries (for EVs and energy storage). Prices are weighted based on the shares of global average annual investment.

Sources: IEA analysis based on company financial reports and BloombergNEF.

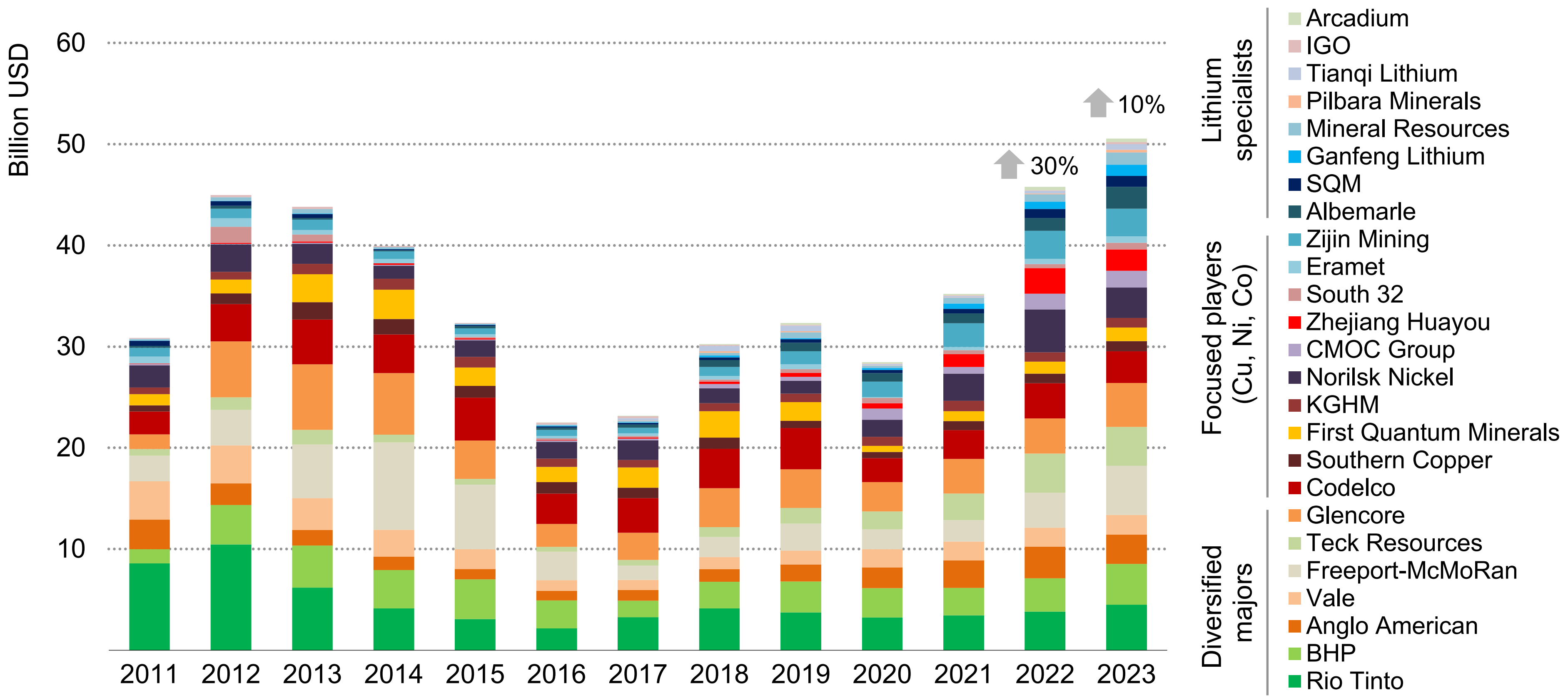
However, low prices resulted in a decline in industry profits by a third in 2023, exacerbated by recent increases in production costs



Notes: EBIT = earnings before interest and taxes. Production case cost is based on the weighted average value for the assets in the 75th quartile.
Sources: IEA analysis based on company financial reports and S&P Global.

Investment in critical mineral mining grew by 10% in 2023, a smaller increase than seen in 2022, as price declines placed pressure on producers' financial capacity

Capital expenditure on nonferrous metal production by major mining companies, 2011-2023

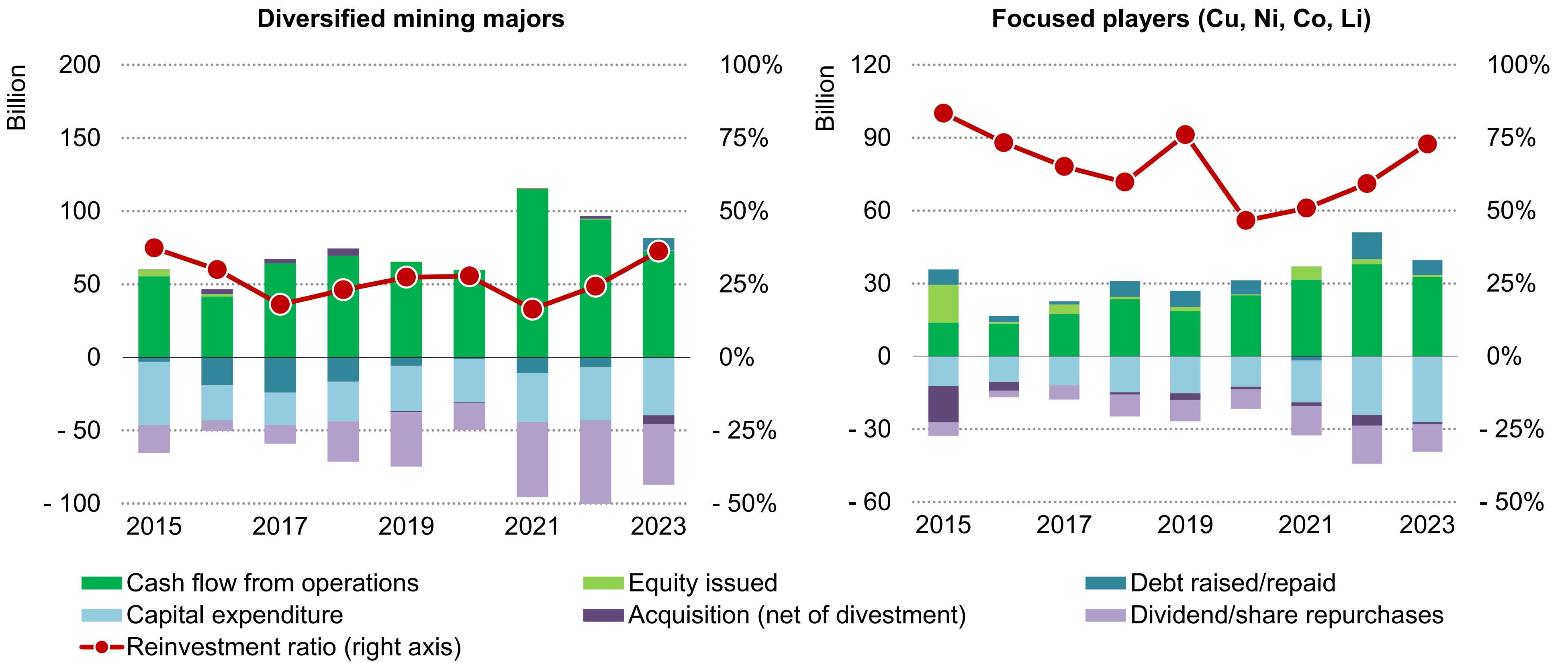


Notes: Co = cobalt; Cu = copper; Ni = nickel. For diversified majors, capex on the production of iron ore, gold, coal and other energy products was excluded. Nominal values. The results for Arcadium start from 2016.

Source: IEA analysis based on company annual reports and S&P Global.

Diversified mining majors are taking a measured approach to investment; specialist players are taking on more risks in pursuit of future growth, albeit with reduced new debt issuances

Cash generation and disposition trends by major mining companies, 2015-2023

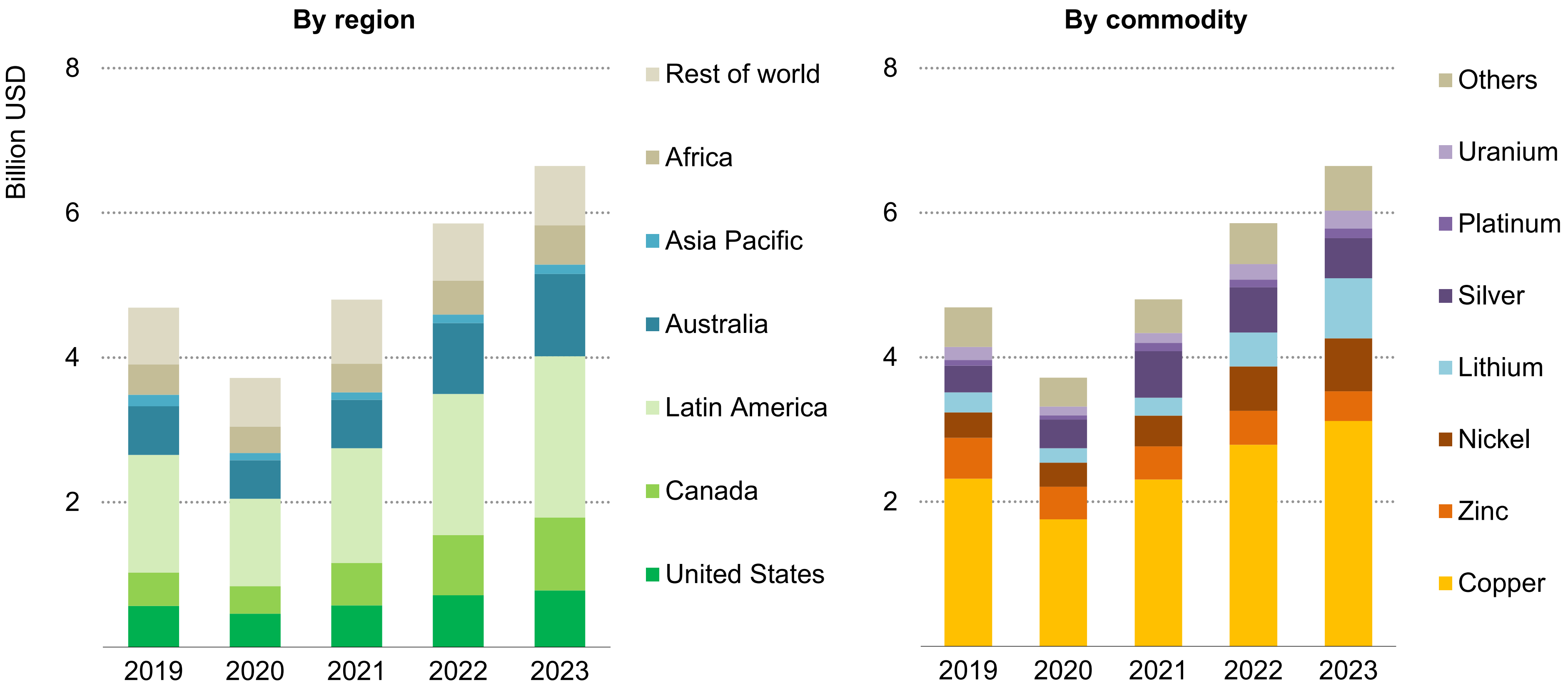


Notes: Excludes investment in marketable securities and others. Capital expenditure covers all commodities, including nonferrous metals. Reinvestment ratio investment = capital expenditure in nonferrous metal production as a percentage of operating cash flow.

Sources: IEA analysis based on company annual reports and S&P Global.

Exploration spending increased by 15% in 2023, driven by Canada and Australia; despite headwinds from falling prices, lithium exploration spending continued to surge by nearly 80%

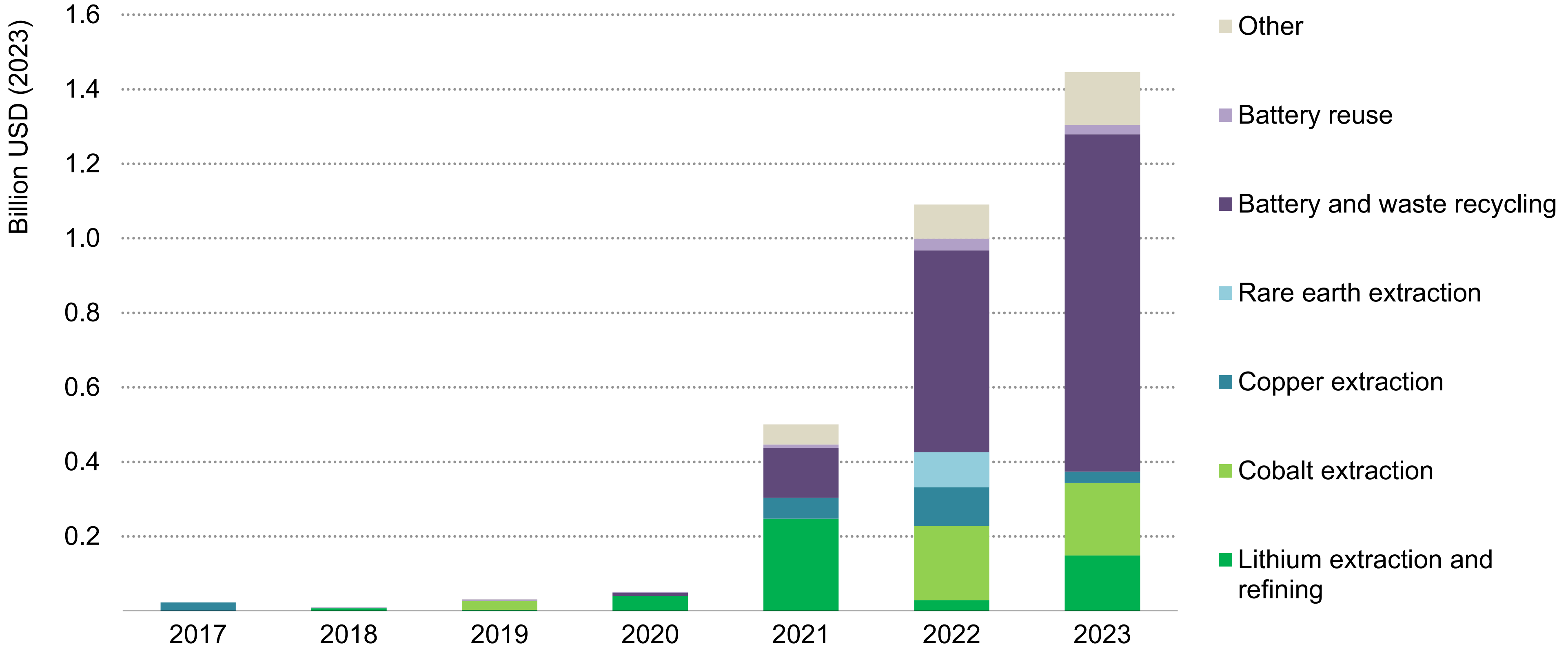
Exploration spending for selected nonferrous mineral resources, 2019-2023



Notes: Excludes budgets for iron ore, coal, aluminium, gold and diamonds. Others comprise rare earth elements, potash/phosphate and many other minor metals.
Sources: IEA analysis based on S&P Global.

Venture capital investment in the critical mineral sector continued to rise in 2023, with significant growth in battery recycling offsetting reductions in mining and refining start-ups

Early- and growth-stage venture capital investment into critical mineral start-ups, 2017-2023



Note: The USD 450 million deal for Energy Exploration Technologies was excluded from the 2022 records as it was subject to the initial public offering process in 2024. This adjustment resulted in a lower 2022 figure compared with the previous year's Critical Minerals Market Review 2023.

Source: IEA analysis based on Cleantech Group i3 database.

Two sides of price declines: A boon for clean energy deployment but a bane for investment and diversification?

Lower prices have contributed to cost reductions for a number of clean energy technologies, although they were not the only factor. Substantial increases in manufacturing capacity, especially in China, have also driven a decrease in prices of clean energy equipment in 2023.

Following two years of rise, IEA's global Clean Energy Equipment Price Index (CEEPI) reveals that prices eased considerably during 2023, with the fourth quarter of 2023 reaching the index's lowest level. The CEEPI tracks price movements in a global basket of solar PV modules, wind turbines, lithium-ion batteries for EVs and battery storage, weighted by shares of investment. Solar PV module prices saw a strong decline as Chinese exports of cells and modules reached 255 GW in 2023, over three times the 2019 level. Price pressures in the wind turbine industry have somewhat eased although prices remain high for non-Chinese producers. After an increase in prices in 2022, battery pack prices also dropped by 14% in 2023. The main driver was a major reduction in prices of critical minerals, as well as an increase in production capacity.

While the low-price environment may foster additional deployment of clean energy technologies in the medium term, it currently presents challenges for producers' financial performance. Industry revenues declined by 10% in 2023 while operating profits plummeted by 34%. Free cash flow also decreased by over 40%, constraining the industry's ability to allocate significant capital for future growth. These challenges have been exacerbated by increases in production costs in recent years. Since 2020, production cash costs for copper, nickel, and cobalt have all trended upwards, with marginal declines in 2023. Between 2020 and 2023, production costs increased by 6% per year for copper, 11% for nickel and 13% for cobalt. Royalties were the largest contributor for copper and nickel, and costs related to energy and reagents were the main driver across the materials.

This triggered a flurry of announcements to put capacity into maintenance and suspend operations (suspension does not mean a permanent closure). While many high-cost producers and new entrants are feeling the impact of the price crash, numerous established assets are still profitable in the current price environment. This suggests that, while prices may rebound as the destocking cycle ends, significant increases could be restrained by growing supplies in the near term. Consequently, this could lead to further geographical concentration of production, as today's dominant suppliers typically operate at the lower end of the cost curve.

Against this backdrop, we have assessed the combined investment levels of 25 major mining companies with substantial involvement in developing minerals essential for the energy transition. These companies encompass diversified mining majors and specialised developers focused on specific energy transition minerals such as copper, nickel, cobalt, and lithium.

Our assessment suggests that investment in critical minerals mining grew by 10% in 2023 (6% when adjusted for inflation), a smaller increase compared with the 30% growth in 2022. While investment spending by diversified majors increased by 15%, investment by lithium specialists saw a sharp rise by 60%, despite headwinds from weak prices.

Exploration spending grew by 15% in 2023, with Canada and Australia registering the largest increases, followed closely by Africa. Spending for lithium exhibited an impressive 80% increase despite challenging market conditions, followed by platinum and nickel.

In 2023, companies allocated approximately 50% of the generated cash to investment, while the remainder flowed back to shareholders and lenders through dividends, share buybacks and debt repayment. Diversified mining majors appear to take a more measured approach to investment, whereas specialist players focusing on specific minerals allocated a greater portion to growth investment, although noticeable reductions in new debt issuances were observed.

As venture capital (VC) investors look for new opportunities across EV supply chains, battery recycling and critical mineral extraction and refining continued to gain momentum. VC investment in the battery recycling space expanded significantly in 2023, notably driven by a USD 540 million round of growth equity funding to United States-based Ascend Elements. Investment in mining and refining start-ups contracted by 12% to USD 375 million in 2023. Cobalt extraction attracted nearly USD 200 million in 2023. Lithium extraction and refining attracted USD 150 million, much higher than the dip of 2022 but still below the record year of 2021.

Notable critical mineral deals in 2023 included USD 50 million series A investment by Canada-based Summit Nanotech to scale its more sustainable lithium extraction technology. In the United States, Kobold Metals raised USD 195 million in growth equity to expand cobalt extraction, Energy Exploration Technologies raised USD 50 million for direct lithium extraction from GM Ventures, and Atlas Materials raised USD 27 million in seed money to develop nickel extraction technologies.

China's approach to mineral investment and security

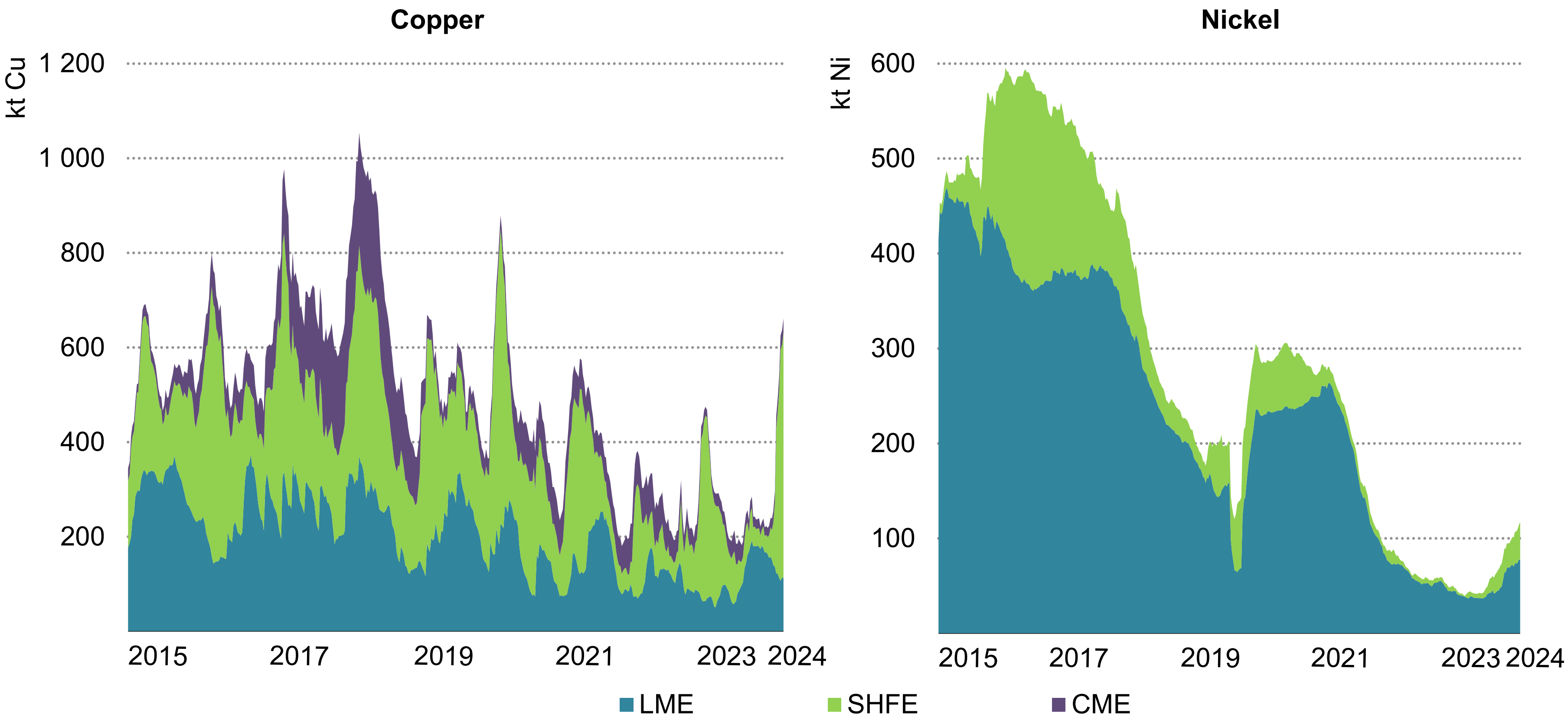
China is the dominant global refiner for critical minerals, processing over half of all lithium, cobalt, graphite and rare earth elements. However, with the exception of graphite and rare earth elements, China is not a major mining centre for these minerals. Therefore, China relies on imports of concentrates and feedstock to supply its refining and subsequent manufacturing operations. The security of supply of these minerals is of a critical concern to China as well.

The importance of these minerals has driven an acceleration of Chinese investment into the mining sector, both domestically and internationally. In 2023 Chinese investment in the metals and mining sector related to the Belt and Road Initiative reached USD 19.4 billion, the highest level in a decade, and a remarkable 160% increase from 2022. China's investment in and acquisition of overseas mines has grown significantly in the past ten years, reaching record levels of USD 10 billion in the first half of 2023 with a particular focus on battery metals such as lithium, nickel and cobalt. Out of the seven lithium assets in Africa that are expected to start production by 2027, five have at least 50% equity ownership by Chinese companies. One of the most significant investments was the Arcadia project in Zimbabwe (by Zhejiang Huayou Cobalt). In Latin America, a consortium led by CATL won a bid in 2023 for a USD 1.4 billion investment to develop Bolivia's resources of lithium. In addition, the Chinese mining major Zijin Mining acquired Canada's Neo Lithium for USD 770 million in 2021 to access the Tres Quebradas lithium project in Argentina. China accounted for 44% of global lithium M&A investments (by value) over the past three years and most of these deals were related to projects in the initial stage of development (initial exploration, feasibility, development). Chinese companies also dominate nickel mining in Indonesia, the largest global supplier of nickel, with a surge of investment over recent years since the complete ore export ban in 2020, including in supporting infrastructure from the Belt and Road initiative. In 2024, majority Chinese-owned producers supply over 80% of Indonesia's battery nickel output. Domestically, China has also ramped up its mining activity, being the third-largest lithium producer. The Xiangyuan lepidolite project (Hunan) is expected to bring 60 kt to 70 kt of lithium carbonates equivalent per year to the domestic market.

Another critical measure from China is the accumulation of national stockpiles, particularly during times of low commodity prices. China's State Reserves Bureau took advantage of the global financial crisis and metal price slump to build up inventories and stockpiles of critical materials, acting as a buffer for the industry against short-term disruption which can also be used as market-balancing volumes to influence prices. In the current lower price and oversupply environment, there is anticipation that China may continue to increase supply, taking market share from other players.

Inventories of key energy transition minerals at major metals exchanges have been trending downwards

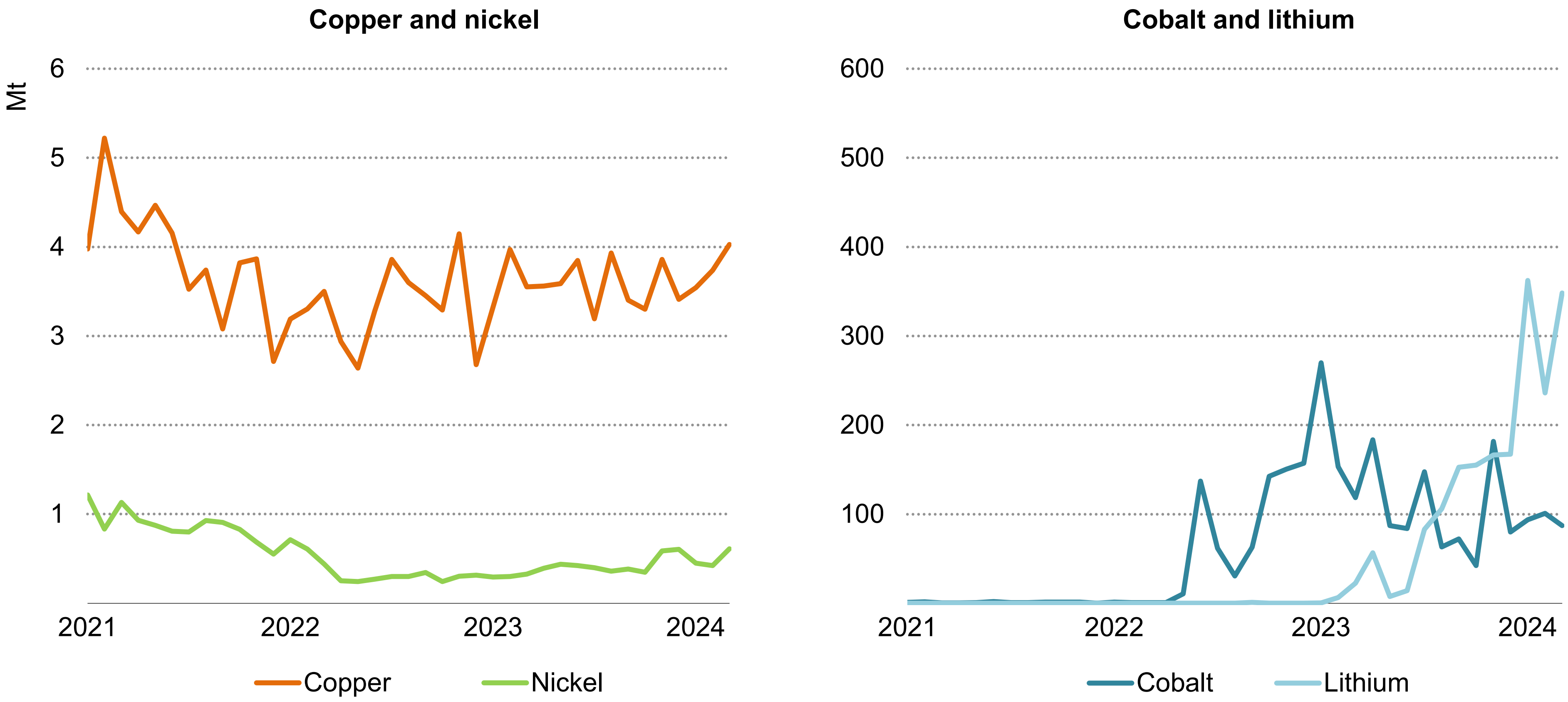
Historical stock levels of copper and nickel at major metals exchanges, 2015-2024



Notes: CME = Chicago Mercantile Exchange. Copper (LME, SHFE, CME); nickel (LME, SHFE). Metals stock is an aggregate volume of deliverables and on warrant.
Source: IEA analysis based on Bloomberg.

Trading volumes for copper and nickel have been declining, while those for cobalt and lithium rise but from much lower levels

Daily trade volume for key battery metals at major exchanges



Notes: Trading liquidity indicates monthly average of daily traded volumes in major metal exchanges. Copper (LME, SHFE, CME); nickel (LME, SHFE); cobalt (LME, CME); lithium (LME, CME).
Source: IEA analysis based on Bloomberg.

Inventories and trading liquidity at major exchanges remain subdued

Inventories and trading volumes of critical minerals at major metals future exchanges provide an indicator on the liquidity. Copper and nickel have been traded for long and more actively in London Metal Exchange (LME), Shanghai Futures Exchange (SHFE), or Chicago Mercantile Exchange (CME) due to their longstanding consumption in industries. With the rising demand for clean energy technologies, cobalt and lithium have been making notable appearances in major metal exchanges in recent years.

Stock

With LME and CME stocks combined, copper stocks have been dwindling to historic lows although there has been a recent surge in SHFE stocks. In recent months, copper stock in the SHFE saw the strongest increase since 2020, reflecting China's high imports to fill up the low inventory from last year and meet demand growth in manufacturing. This high level may subside in the near term, however, as consumption picks up with China's stronger-than-expected manufacturing activity and higher business confidence. While visible stocks at exchanges represent only a fraction of total stocks, their decline suggests a tightening market and limited capacity to absorb supply shocks.

Inventories for nickel, despite the SHFE recording a four-year high in recent months, still dwindles from its historical high level in aggregate terms. The LME saw a rise earlier in 2024 due to the addition of Russian and Chinese nickel. However, a ban on Russian-origin metal introduced in April 2024 may impact this growth going forward.

Trading volume

Trading volumes of copper and nickel on major metals exchanges indicate them as the most liquid among key energy transition minerals due to their longer history of consumption in industries. Liquidity of nickel has yet to recover from the level prior to the LME's contract suspension in March 2022, which created a ripple effect on the SHFE to also suspend nickel contract for a day.

Cobalt and lithium have seen notable growth in trading volumes in the LME and CME over the last two years as their demand trends upwards. As expected cobalt demand rises, trading activity increased on the CME cobalt contract with producers and consumers responding to the narrative. Lithium contracts soared last year with growing hedging activity from traders and industry after its price dropped in 2023. Growing demand for lithium has led market players to hedge from increasing exposure to the volatile commodities market. However, the trading liquidity of battery metals still lags significantly behind that of other bulk materials, despite recent improvements. As it stands, daily traded volume as a percentage of annual production represents less than 1% for lithium and cobalt.

Latest policy developments

Producing countries intensify efforts to secure economic benefits; consumer nations enact significant laws and regulations to ensure an adequate and responsible supply

Laws, regulations, and high-level policies are being reformed and issued globally, given the latest surge in interest for critical minerals projects. From policies included in the 2023 update of the Critical Minerals Policy Tracker, it is clear that producing countries and consumer countries often have different policy objectives. ESG regulations and co-operation agreements are more apparent in developed producer economies and in consumer countries, with some endowed with resources also focusing on financing project development. On the other hand, jurisdictions on the supply side have focused on ensuring economic benefits from their own resources. To boost supply resilience, countries are increasingly working together – both multilaterally and bilaterally – to identify priority projects and strengthen co-operative ties.

Producer policies

While some producing countries already have high-level critical minerals strategies, such as Australia and Canada, more critical minerals strategies are now under development, particularly by new market entrants. For example, the African Minerals Development Centre (ADMC) is developing an African Green Minerals Strategy which will aim to guide African countries as they consider how to exploit their raw materials. Individual countries are also in the process of developing strategies, such as Zambia, which is intending to release a critical minerals strategy in 2024.

Some mineral-producing jurisdictions have created public strategic minerals investment funds. In February 2024, Brazil announced a USD 200 million fund to support both exploration and improvements in ESG practices. In October 2023, Australia expanded its Critical Minerals Facility with a USD 1.3 billion investment, financing extraction and processing projects. Canada's CAD 1.5 billion (Canadian dollars) Strategic Innovation Fund, as part of the CAD 2.8 billion Critical Minerals Strategy, aims to prioritise innovative critical minerals manufacturing, processing and recycling projects.

In Latin America, both Mexico and Chile enacted policies to develop their domestic lithium mining industries. Mexico followed its 2022 Mining Reform with legislative amendments in 2023 that streamlined the mining permitting process and strengthened environmental and social protections. Pertinent amendments include: (i) cancelling concessions for environmental and safety risks; (ii) creating new mining offenses; (iii) empowering the water authority to reduce the industrial water concession for mining operations to ensure enough water for local consumption; (iv) prohibiting mining operations in protected areas; and (v) placing the liability for mining and metallurgical waste on concession holders.

Chile also followed its 2023 National Lithium Strategy with an update to its Mining Royalty Law in 2023. The law established a mining royalty for the exploitation of copper and lithium to distribute economic benefits across the country, along with a legal body to administer it. Included in the law are increases to the tax burden on mining activities specifically for mining operators whose annual sales are predominantly derived from copper and exceed an equivalent value of 50 000 metric tonnes of fine copper, but with a maximum potential tax burden of 45.5% for those with 80 000 metric tonnes and 46.5% for the rest. Revenue from the law (estimated to be USD 450 million) will be distributed to funds such as: (i) a fund to compensate mining communities that have been directly affected by the negative externalities of mining activities (USD 55 million); (ii) a fund for the most vulnerable communities in the country; and (iii) a fund to leverage productive infrastructure investments in the northern regions.

The United States and European Union have proposed reforms to permitting processes to increase domestic mining production and reduce dependency on imports. The Permitting Action Plan outlines key actions, including better internal coordination, tracking of review progress, enhancing outreach and providing technical assistance to affected stakeholders. The Inflation Reduction Act provides funding to various government agencies to hire new personnel and develop tools and guidance to strengthen and accelerate environmental reviews.

Separately, the proposed Critical Raw Materials Act (CRMA) would allow certain projects to be designated as “strategic” that would have a streamlined permitting process. The act lays out criteria for a project to be designated as “strategic,” including whether the project would be implemented sustainably and responsibly. Besides permitting processes, the CRMA would also create a monitoring mechanism to mitigate the risk of supply chain bottlenecks.

In order to meet the policy goal of increasing the amount of local value addition, some producing countries are turning to export restrictions on raw or unprocessed ores. In 2020, Indonesia announced that it would restrict the export of unprocessed nickel. While the World Trade Organization (WTO) ruled against Indonesia’s restrictions following the European Union’s challenge, the lack of a quorum at the WTO Appellate Body has delayed the appeal process indefinitely. In the meantime, Indonesia implemented similar restrictions on bauxite ore in June 2023 and announced restrictions on copper ore expected to be in force in June 2024. Other countries have adopted or are considering adopting similar measures, including Namibia, which banned the export of lithium ore in mid-2023, and Zimbabwe, which banned raw lithium exports in 2023 to attempt to secure value addition.

Other countries in Asia have enacted export restrictions designed to encourage supply and safeguard national interest. China issued export controls last year, such as the export control of gallium- and germanium-related items (in force August 2023) and the export control for graphite-related items (in force December 2023), through which businesses are required to seek export licences from the government.

Consumer policies

At the same time, consumer countries have developed laws and regulations targeting sufficient supplies of responsible critical minerals. This has been particularly true in countries with large downstream manufacturing industries, which rely on a supply of these minerals. Japan announced a policy on initiatives for ensuring stable supply of critical minerals in 2023, which aims to secure supplies for its battery manufacturing goals and provides subsidies for exploration, feasibility studies, mine development, smelting and research and development to develop supplies. Korea announced a list of 33 critical minerals and 10 strategic critical minerals, of which the latter will be prioritised to stabilise the supply chain of high-tech industries such as semi-conductors and secondary batteries. The country is also seeking to deepen co-operation with 30 identified resource-rich countries to secure mineral deals.

As a next step to minerals lists, strategic plans have been issued over the last year which focus on specific needs based on countries' priority minerals. Japan released a Resource Diplomacy Guidance, which outlines the country's approach to minerals and producing countries and specifies the priority minerals and countries from which it intends to source.

Some countries also make financing support available for overseas projects through direct equity investments or sovereign wealth funds, such as in Japan, Saudi Arabia and China. The United Kingdom also pledged USD 1 million to identify bankable projects in processing and midstream value addition in 14 African countries. In the European Union, France set up a critical minerals and metals equity fund managed by InfraVia and backed by up to USD 500 million in government funds. The fund will function as a minority shareholder of industrial and mining stakeholders across the value chain, and is focused on securing offtake contracts to support French and European industries, with a commitment to adhere to high social and environmental standards in collaboration with various financing partners.

In the last year, consumer countries have also made significant strides to integrate policies targeting the sourcing of responsibly produced minerals. In the European Union, the Corporate Sustainability Reporting Directive (CSRD) and the Corporate Sustainability Due Diligence Directive (CSDDD) enhance corporate accountability regarding ESG performance. The CSRD will make it mandatory for all large European companies and companies listed on EU-regulated markets to report on selected ESG metrics by 1 January 2024. The CSRD is working to release sector-specific requirements, including for the mining sector. Complementary to the CSRD, the CSDDD imposes mandatory human rights and environmental due diligence requirements on large companies, compelling them to identify, prevent, and mitigate adverse impacts in their operations and entire value chain. This includes obligations for companies to establish and update a climate transition plan aimed at aligning business strategies with the Paris Agreement and the European Union's 2050 climate neutrality target.

International co-operation

A number of countries work through the Minerals Security Partnership (MSP) to collaboratively strengthen security of supply. In 2024, the MSP welcomed Estonia as its newest member, bringing participation to 14 countries plus the European Union. This effort is focused on supporting the development of strategic projects. In late 2023 and early 2024, the MSP countries announced progress in raising financing or securing offtake agreements for a number of projects including ones targeting manganese, nickel, and graphite.

There has been a growing trend of countries announcing bilateral or multilateral strategic partnerships focused on critical minerals, some of which integrate strong ESG standards. Recent examples include a Statement of Intent between Australia and the United Kingdom and the United Kingdom and South Africa partnership on minerals for future clean energy technologies, Strategic Partnerships between the European Union and Chile, the Democratic Republic of the Congo and Zambia, and a memoranda of understanding between Canada and Korea. The specific content of these partnerships varies, but they generally are aimed at strengthening bilateral ties and providing vehicles for countries to support individual projects. That said, the specific impact of individual partnerships depend on how they are implemented, which is difficult to gauge in many cases as many partnership arrangements are not made public.

In the next year, we expect to see more bilateral agreements and strategic partnerships emerge with a focus on either securing or developing critical minerals supplies. The European Union is looking to expand its network of Sustainable Investment Facilitation Agreements of Free Trade Agreements. Emerging producer countries are also expected to continue signing agreements to boost investment into critical minerals projects in their countries. In 2023, economic ministers from France, Germany, and Italy aligned to enhance the sustainable supply chain of critical raw materials by setting specific targets for extraction, processing, and recycling, and by expanding the list of strategic materials to include aluminium. They committed to enforcing stringent ESG criteria and established a dedicated working group to ensure effective implementation of these initiatives.

Recycling policies

Strategic plans have incorporated measures aimed at boosting rates of battery recycling, and 2023 saw a notable uptick in policies aimed at increasing the recycling of clean energy technologies to secure critical minerals from both consumer and producer countries. The European Union's Critical Raw Materials Act will require member states to identify, adopt and implement measures to improve the collection and recycling of critical mineral-rich waste, as well as investigate the potential for recovery of critical raw materials from extractive waste in active and historic mining sites. Norway's Mineral Strategy, released in June 2023, also includes focus on a circular economy, requiring new mineral projects to present a circular business plan.

Specific measures to increase recycling have come in the form of investment into research and development and waste collection, such as the United States' USD 192 million of funding for increasing recycling rates and research and development into battery recycling technologies from consumer products. There has also been project-specific funding, with the European Commission providing battery producer BASF with a USD 110 million grant to support a battery recycling project in Spain.

Example of harmonisation of ESG standards: Consolidated Mining Standard Initiative

In recent years, there has been a growing chorus of calls for greater harmonisation or convergence of existing ESG standards and sustainability initiatives. Against this backdrop, the International Council on Mining and Metals (ICMM), The Copper Mark, the Mining Association of Canada and the World Gold Council announced in November 2023 that they will seek to consolidate their individual standards into one global responsible mining standard with a multi-stakeholder oversight system. The collaboration aims to simplify the landscape of standards and sustainability initiatives and drive performance improvements at scale.

The organisations have expressed their expectation that the consolidation process will combine the best attributes of each individual standard and be implementable by any mine operator at site-level with a commitment to mine responsibly, with substantive prescriptive performance requirements, robust independent assurance and a multi-stakeholder governance model. The consolidated standard will cover more than 20 performance areas grouped under Ethical Business Practices, Worker and Social Safeguards, Social Performance, and Environmental Stewardship. The organisations have announced that they will collect input from all interested stakeholders, including affected communities, Indigenous peoples, civil society organisations, industry, investors, downstream customers and government.

With the proposal expected to go out for public consultation in mid-2024, the goal is to release the standard during 2025. Once finalised and launched, the consolidated mining standard would be expected to be adopted by members of the organisations – around 80 mining companies with 700 operations spanning 60 countries.

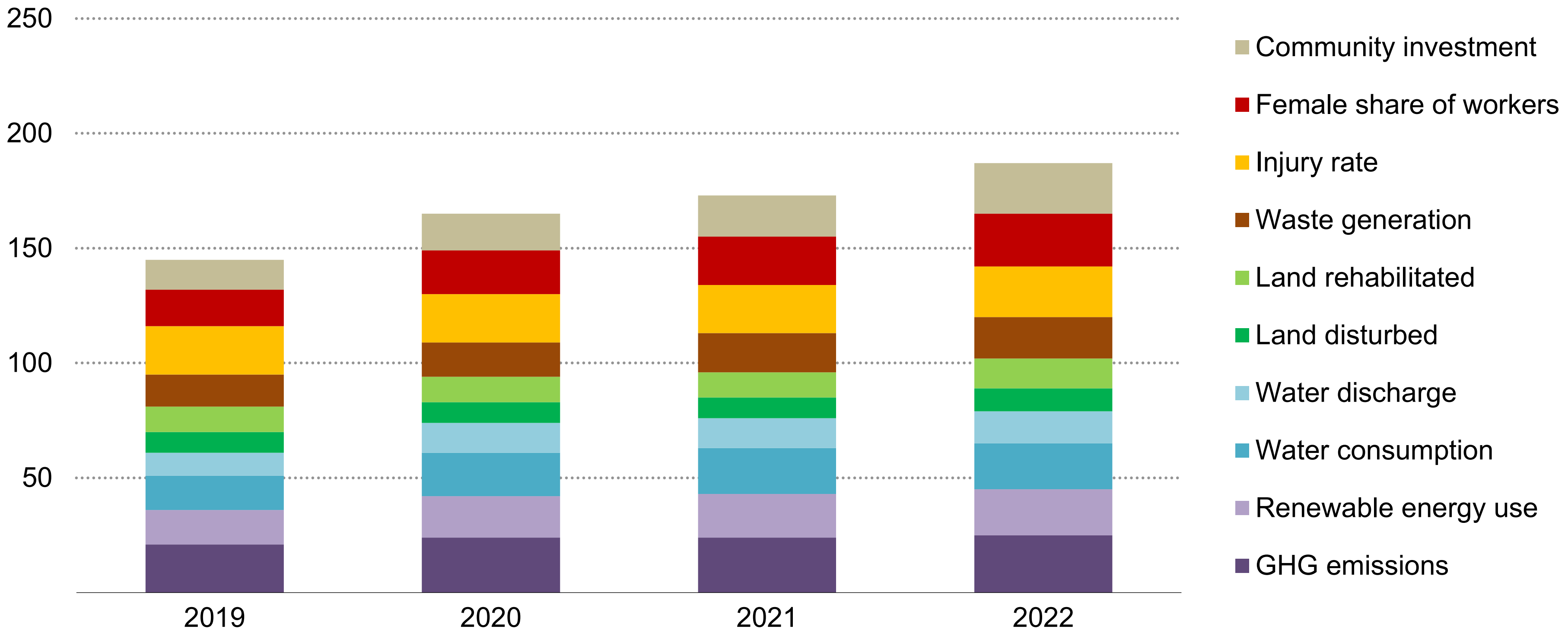
While harmonising standards provisions may facilitate practical application, addressing key issues remains essential. Firstly, ensuring credibility necessitates a robust multi-stakeholder governance model. Secondly, ensuring comparability requires a transparent, uniform reporting structure. Thirdly, harmonised standards must remain aligned with relevant international frameworks and avoid a “lowest common demoninator” outcome.

A combined standard may also be a step towards comparable data that governments and civil society organisations can easily track to assess the mining industry’s ESG performance. However, high ESG performance should still be contingent on the jurisdiction of mining operation as well as the importing country.

ESG performance tracking

The industry is making progress on ESG reporting

Number of companies with a strong presence in energy transition minerals reporting selected ESG indicators



Note: GHG emissions considers reporting on total scope 1 and 2 greenhouse gas emissions; water use considers water consumption. Data from 25 major companies were reviewed, so the maximum value for each of the ten selected ESG indicators and commitments is 25, with a potential overall total of 250.

Source: IEA analysis based on the latest sustainability reports of Albemarle, Allkem and Livent (Arcadium Lithium), Anglo American, BHP, CMOC Group, Codelco, Eramet, First Quantum, Freeport Mc-MoRan, Ganfeng Lithium, Glencore, IGO, KGHM, Mineral Resources, NorNickel, Pilbara Minerals, Rio Tinto, South32, Southern Copper, SQM, Teck Resources, Tianqi Lithium, Vale, Zhejiang Huayou, and Zijin Mining Group Co. Ltd.

Current company reporting does not allow for an industry-wide assessment of progress towards sustainable and responsible supply, but ESG performance is slowly becoming clearer

Critical mineral supply chains cannot be truly secure, reliable and resilient unless they are also sustainable and responsible. The mining industry does not have the best track record managing ESG impacts, but many players are aiming to change that. Our assessment of company progress across various ESG dimensions – based on the public sustainability reports and commitments published by 25 major companies that have a strong presence in critical minerals supply chains – shows progress in reporting and growing commitments.

All of these companies report efforts to improve their ESG performance, but goals vary starkly. About 20 have pledged to achieve net zero emissions by or before 2050, with the remaining yet to establish a firm long-term emissions target. Most net zero targets apply only to emissions from direct operations (scope 1) or purchased energy and heat (scope 2), leaving out other emissions from the industry's value chains (scope 3). Around five companies have established targets to reduce absolute emissions by 35% or more by 2030 or earlier. Many companies refer to a reduction in emissions intensities to 2030 or have established reduction targets only for 2035. Several industry players have also committed to other ESG goals, such as causing no net loss of biodiversity or limiting the amount of freshwater used in mining.

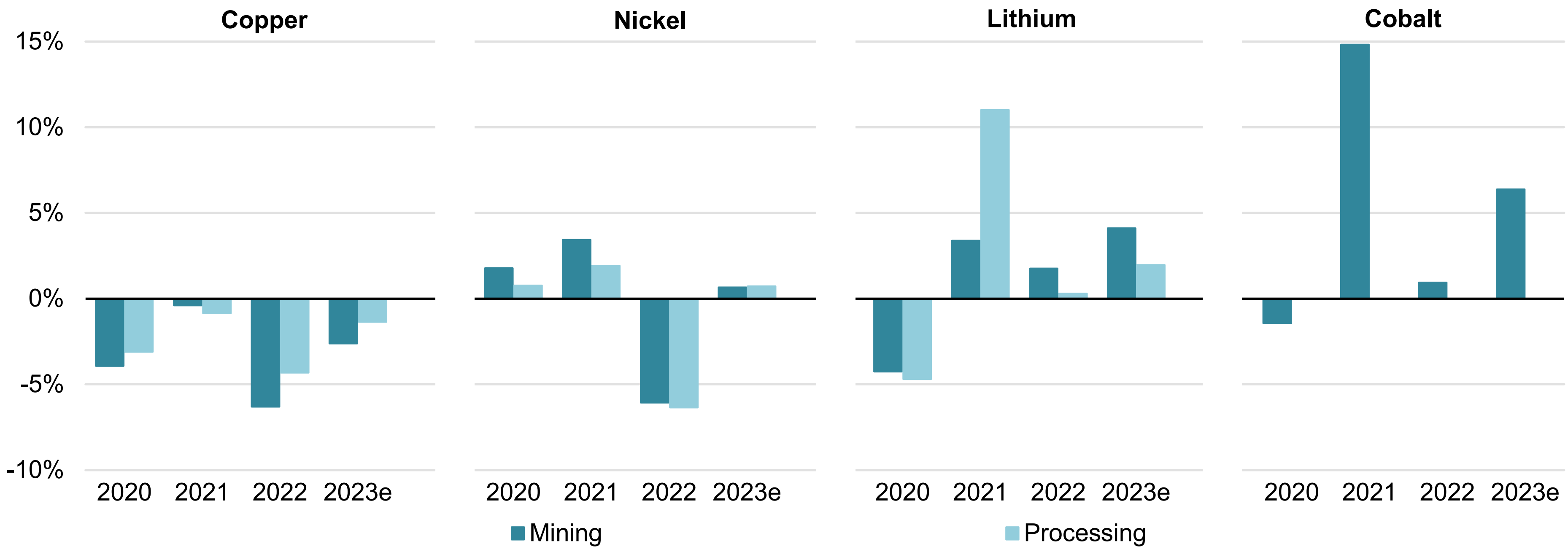
These commitments are being followed by better reporting of ESG practices. Our assessment revealed an increase in the availability of data for the latest years, indicating the industry is putting more effort into tracking its performance. The number of companies reporting investment in communities, female share of workers and water discharge increased by 40% or more during this period. All players now report GHG emissions and nearly 90% report share of female workers, injury rates and community investment.

Nevertheless, an industry-wide assessment of progress on ESG still faces many challenges. Only around ten companies published data on land area disturbed and rehabilitated, and less than five reported on involuntary resettlement. Few operators detail risks related to their supply chains, such as potential child labour, or provide clear information on contract disclosure.

ESG reporting varies substantially in both consistency and breadth. Most companies aggregate their reported data in some form or another, often at the company level, making it difficult to compare performance for specific minerals or regions. Less than five companies disclosed site-level data consistently in their reports; positive examples include Aracdium Lithium, Codelco, and First Quantum. Units and scope of reporting also vary, sometimes even within the same report (e.g. for different operational units).

Climate pledges are driving decarbonisation measures, particularly in copper supply, but overall performance on emissions is still far from showing robust reductions

Annual changes in GHG intensities for selected minerals

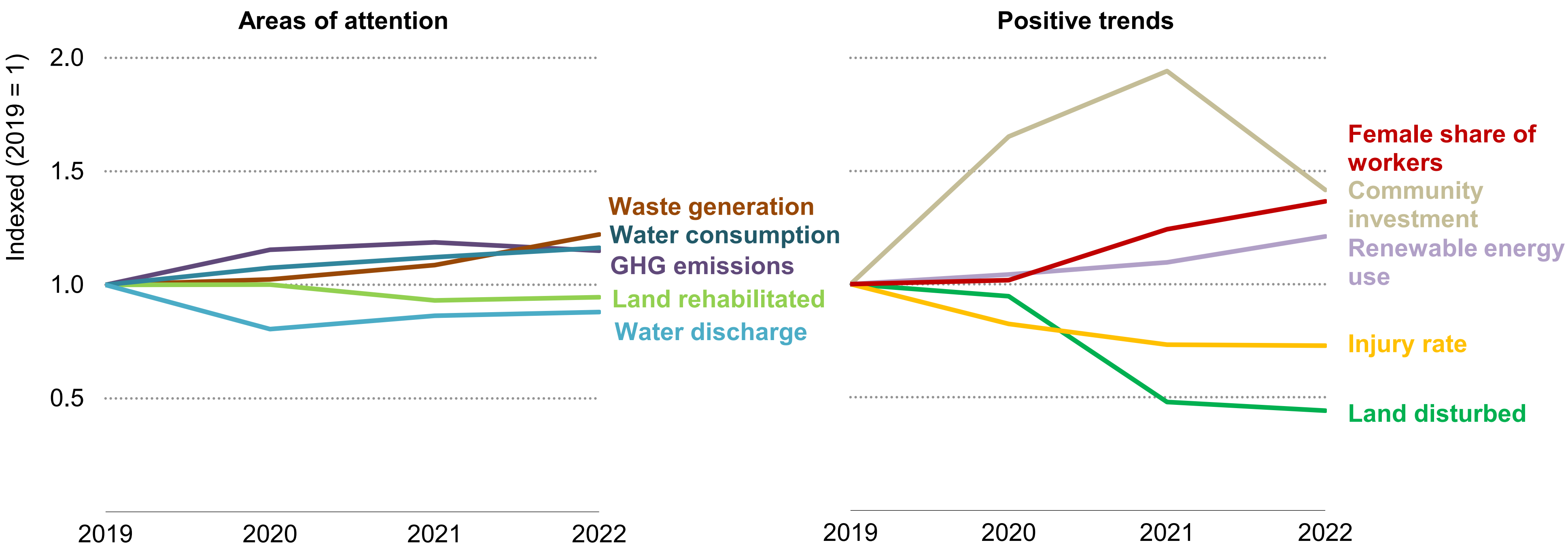


Notes: 2023e = estimated values for 2023. Mining covers scope 1 and 2 greenhouse gas emissions intensity (measured in tonnes of CO_2-equivalent per tonne of mineral). Processing covers scope 1, 2 and 3 greenhouse gas emissions intensities, usually up to refined metal or first saleable product. No data available for cobalt processing.

Source: Data provided by Skarn Associates.

Sustainability reporting paints a mixed ESG picture, with substantial room for improvement

Selected ESG indicators, 2019-2022



Notes: Aggregated data for 25 major companies that have a strong presence in critical minerals supply chain. Considers reported data for all operations. Indicators are calculated per tonne of mineral produced – except for injury rate, water recycling and female share of workers – which reflect the weighted average by production.

Source: IEA analysis based on the latest sustainability reports of Albemarle, Allkem and Livent (Arcadium Lithium), Anglo American, BHP, CMOC Group, Codelco, Eramet, First Quantum, Freeport-McMoRan, Ganfeng Lithium, Glencore, IGO, KGHM, Mineral Resources, NorNickel, Pilbara Minerals, Rio Tinto, South32, Southern Copper, SQM, Teck Resources, Tianqi Lithium, Vale, Zhejiang Huayou, and Zijin Mining Group Co. Ltd.

Key ESG challenges and trends

The sustainable and responsible supply of critical minerals depends on a myriad of interrelated practices, from water stewardship to emissions management, engaging with communities and ensuring safe labour standards, a fair share of benefits, protecting biodiversity, reducing waste, and much more. The industry is making progress on several of these fronts. From 2019 to 2022, reported injury rates decreased by nearly 30%, investments in communities surged from USD 0.3 billion to USD 1 billion, and the average share of female workers went from just over 15% to 20%. Data are more sparse for other indicators, but available information suggests improvements in the amount of waste being recovered through reprocessing and reuse and the share of water that is being recycled or re-used in industry facilities. These positive trends do not hold for all companies, but reflect widespread industry efforts.

On the other hand, there are many areas where progress has been limited and some even show negative trends. The amount of waste generated per unit of mineral produced increased by over 20% from 2019 to 2022, potentially due to the development of lower-grade resources. Reported water consumption increased by around 25% during this period even in the face of high supply risks related to droughts for copper and other minerals. Similarly, indicators related to land rehabilitation, effluent discharge and GHG emissions did not exhibit visible improvements despite growing ESG commitments.

Voluntary sustainability standards can help actors improve performance and earn ESG credentials. These include the ICMM's Mining Principles and performance expectations, the Initiative for Responsible Mining Assurance's Standard for Responsible Mining, Canada's Towards Sustainable Mining, the Responsible Minerals Initiative and the Copper Mark's Risk Readiness Assessment Criteria Guide. While these standards can all lead to increased transparency and sustainability performance, there are major differences between the overall stringency of requirements, the scope of their application, the approach to compliance and reporting, uptake, and in oversight and assurance systems. Greater transparency, due diligence, harmonised approaches to credibility and appropriate incentives are needed to untap their full potential.

Material traceability services are also on the rise. This involves working with suppliers to track sources and related impacts up to the point of incorporation into an end product. It can allow an assessment of risks and ESG performance along the supply chain, contributing to increased mineral security. Policymakers and companies, however, should be aware of the limitations of end-to-end product traceability. Due to the nature of both aggregation and blending in mineral supply chains, particularly at the smelting and refinery stage, traceability is not always possible or practical. Traceability mechanisms can be paired with a risk mitigation approach for better ESG due diligence.

2. Demand and supply outlook for critical minerals

Introduction

The world is on a journey towards achieving net zero emissions, and has declared its ambition to limit global warming to 1.5 °C, which would mean completing this journey already by 2050. Whichever pathway this journey eventually takes, it will require a massive expansion of clean energy technology deployment, along with reliable supplies of critical minerals. While short-term market dynamics are crucial, medium- to long-term perspectives on critical minerals demand and supply are equally important to ensure that clean energy transitions are not hindered by supply chain bottlenecks. There are numerous questions that need to be addressed. How fast might demand for critical minerals grow under different assumptions about the strength of climate action? Can we ensure sufficient volumes of critical minerals to support the acceleration of energy transitions? What are the key risk areas that policymakers need to monitor, and how do prospects vary by mineral? Where are today's project developments leading us in 2030 and beyond, in terms of diversified supplies? What role do environmental, social, and governance (ESG) considerations play in shaping future market developments?

This chapter addresses these crucial questions by providing a comprehensive outlook for demand and supply for key energy transition minerals, namely copper, lithium, nickel, cobalt, graphite and rare earth elements. Additionally, we also briefly discuss key issues around aluminium, manganese, silicon, phosphate and platinum group metals (PGMs).

Demand projections encompass both clean energy applications and other uses, focusing on the three IEA scenarios – the Stated Policies Scenario (STEPS), the Announced Pledges Scenario (APS) and the Net Zero Emissions by 2050 (NZE) Scenario – with a particular focus on the latter two climate-driven scenarios in which national and/or global climate goals are achieved (see “Introduction” for scenario descriptions). More details on the methodology can be found in the Annex.

Supply projections are based on a detailed review of all announced projects. We have constructed two supply scenarios – a base case and a high production case. The **base case** includes production from existing assets and those under construction, along with projects that have a high chance of moving ahead as they have obtained all necessary permits, secured financing, and/or established offtake contracts. The **high production case** additionally considers projects at a reasonably advanced stage of development, seeking financing and/or permits. In many instances, these projects are in the process of conducting feasibility studies, and in some cases these assessments are already complete.

Neither case considers projects that are in very early stages of development, or includes theoretical projects for which resources might be adequate but which have not been proposed. For these reasons, our focus on the supply side is on the period to 2040.

Based on these two supply scenarios, we assess how today's geographical concentration evolves over time, for both mining and refining, and how expected supply compares with primary supply requirements in climate-driven scenarios (total demand net of expected contributions from secondary supply and reuse). In some cases, we highlight potential gaps between expected supplies and material requirements in climate-driven scenarios.

We do not attempt to close these gaps by introducing additional projects beyond those already underway or being considered. Climate-driven scenarios, the NZE Scenario in particular, reflect many demand-side measures such as higher recycling rates, some behavioural changes (e.g. wider use of public transport in relation to private transport, policies to promote optimal sizing of cars), but we recognise that there is a possibility of additional demand-side measures or technological innovation which could contribute to reducing demand further.

The aim of the exercise is to provide a framework for assessing progress towards achieving global energy security and climate goals and risks that may arise along the way.

There remain considerable uncertainties over how market balances evolve in practice. On the demand side, it should be noted that the world is not yet on track for the outcomes in the APS or the NZE Scenario; doing so will require significant additional efforts by policymakers and industries alike.

Where gaps are identified between future demand and supply, these may potentially be closed by developing additional projects, scaling up recycling further, and promoting a range of material efficiency measures beyond what are already assumed. The results should not be interpreted to mean that energy transition goals are unattainable due to material constraints.

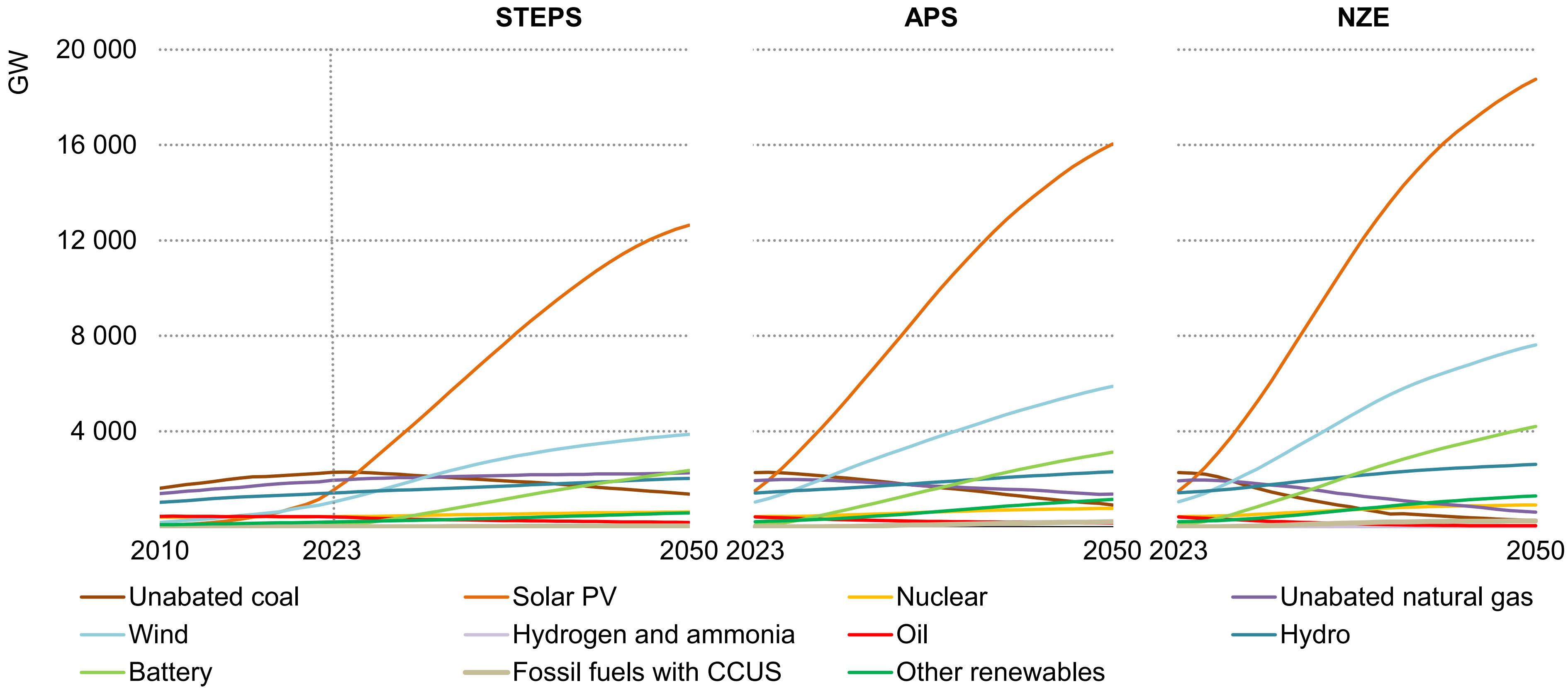
This chapter starts a brief review of projected mineral demand in the clean energy sector and presents overall findings of the detailed outlook for key energy transition minerals. Each mineral section then presents demand and supply projection results and discusses key issues underpinning long-term market developments.

The analysis in this chapter is complemented by the assessment in Chapter 3, which provides structured “clean energy transitions risk assessments” across four major dimensions – supply risks, geopolitical risks, barriers to respond to supply disruptions, and exposure to ESG and climate risks. These assessments aim to help policymakers identify potential areas of weakness for each material in supporting their energy transition goals.

Mineral demand for clean energy technologies

Solar PV and wind capacity surge ahead, moving well beyond any other source; renewables account for the majority of capacity additions in every region in all scenarios

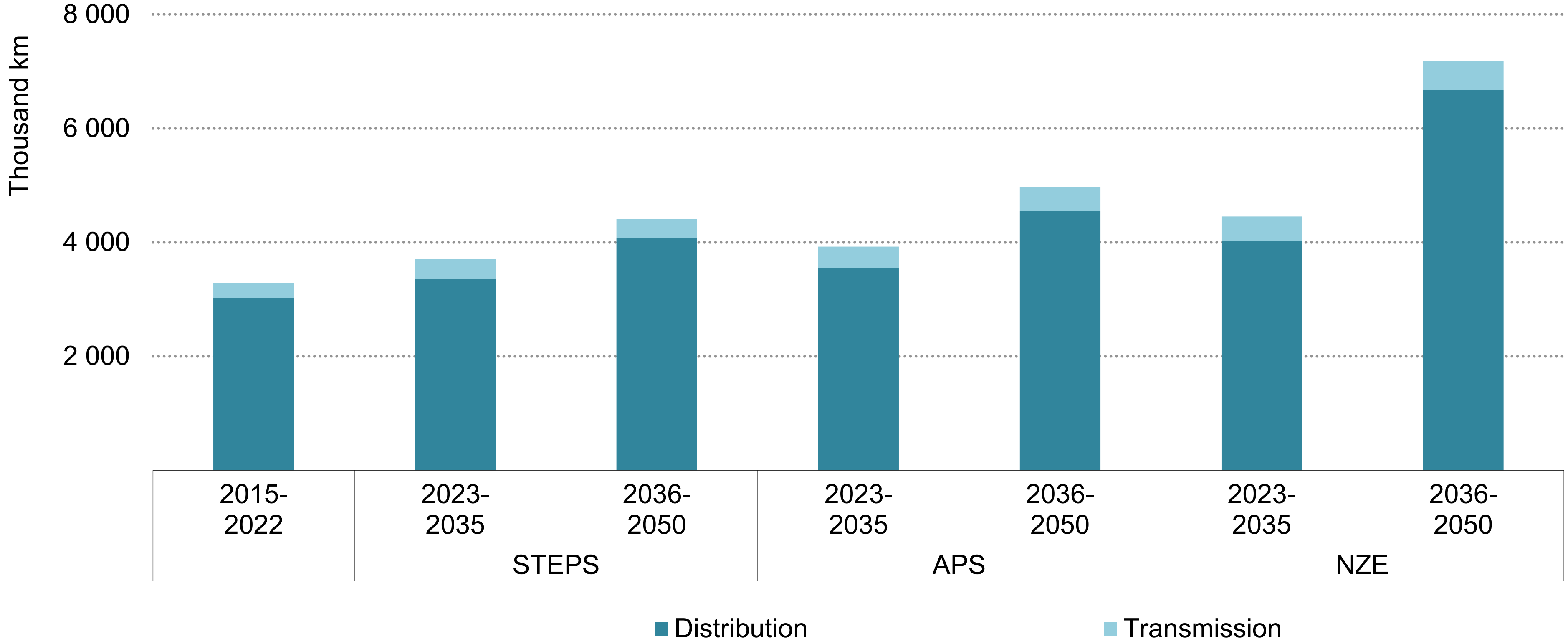
Global installed electricity capacity by source and scenario



Note: CCUS = carbon capture, utilisation and storage.

The acceleration of renewable energy deployment necessitates a substantial expansion of transmission and distribution networks, pushing up demand for copper and aluminium

Average annual grid line additions by scenario



Note: Includes both new additions and replacements.

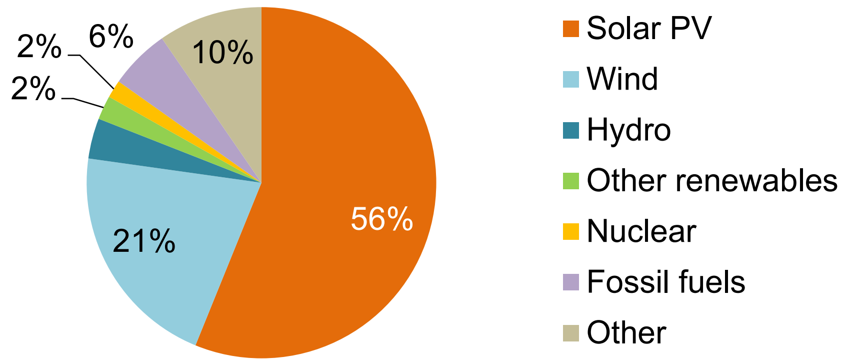
Rising deployment of renewables and grids is set to raise demand for critical minerals

The growth of power generation capacity from low-emissions sources accelerates in all three scenarios. Renewables account for the majority of capacity additions in every region over the outlook period. By far, wind and solar PV are the largest contributors to this development, and total installed solar PV capacity in particular far outstrips that of any other source in all scenarios.

By 2026, solar PV becomes the largest contributor to installed electrical capacity in the STEPS, followed by wind. This growth trajectory would see global renewable capacity increase to 2.5 times its current level by 2030, a major expansion but one that falls short of the tripling goal agreed at COP28. Government actions to facilitate grid connections, and resolve permitting, policy and financing issues, are needed to accelerate growth. In the APS, low-emissions power sources account for almost 80% of total power capacity additions in 2030, with solar PV making up 55% and wind 20%. Annual solar PV and wind capacity additions grow by two times to 2050 in the APS and by over two and a half times in the NZE Scenario.

The acceleration of renewable energy deployment calls for modernising distribution grids and establishing new transmission corridors to connect renewable resources that are far from demand centres such as cities and industrial areas. Around 3 000 GW of renewable power projects are waiting in grid connection queues – equivalent to five times the amount of solar PV and wind capacity added in 2022. Due to aged infrastructure and a high share of variable renewables in the system across the globe, reaching national goals also means adding or refurbishing a total of over 80 million km of grids by 2040, the equivalent of the entire existing global grid. This would underpin significant growth of copper and aluminium demand for cables. Grid investment growth in the past decade has occurred mainly in the People's Republic of China (hereafter "China") and advanced economies. China alone accounted for over one-third of the world's transmission grid expansion in the past decade, connecting, among other places, the eastern load centres to the renewable energy-rich provinces.

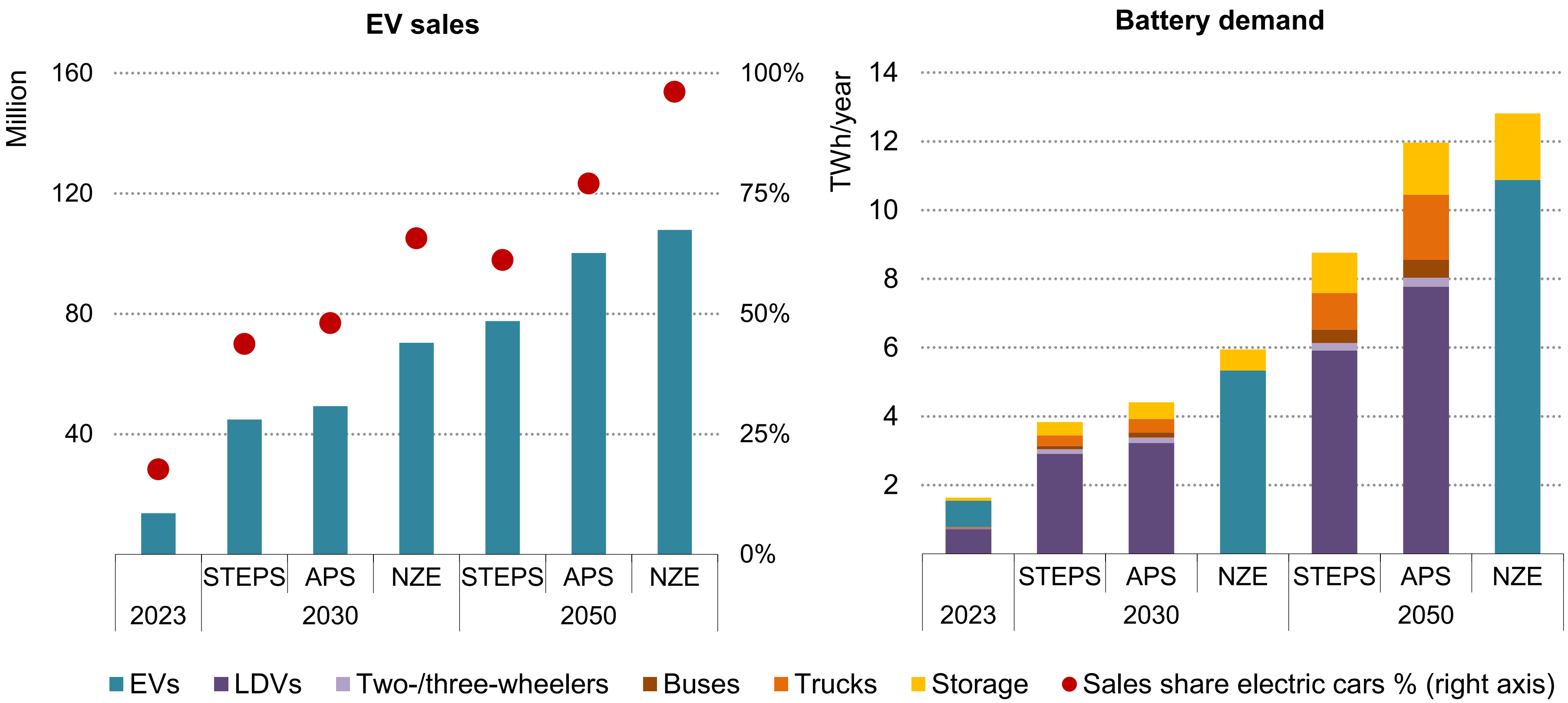
Share of cumulative power capacity addition by source in the APS, 2024-2030



Note: Other include batteries, hydrogen and ammonia.

Battery demand increases fivefold to 2030 and fourteen-fold to 2050 to meet climate pledges driven by EV sales and growth in deployment of electric trucks

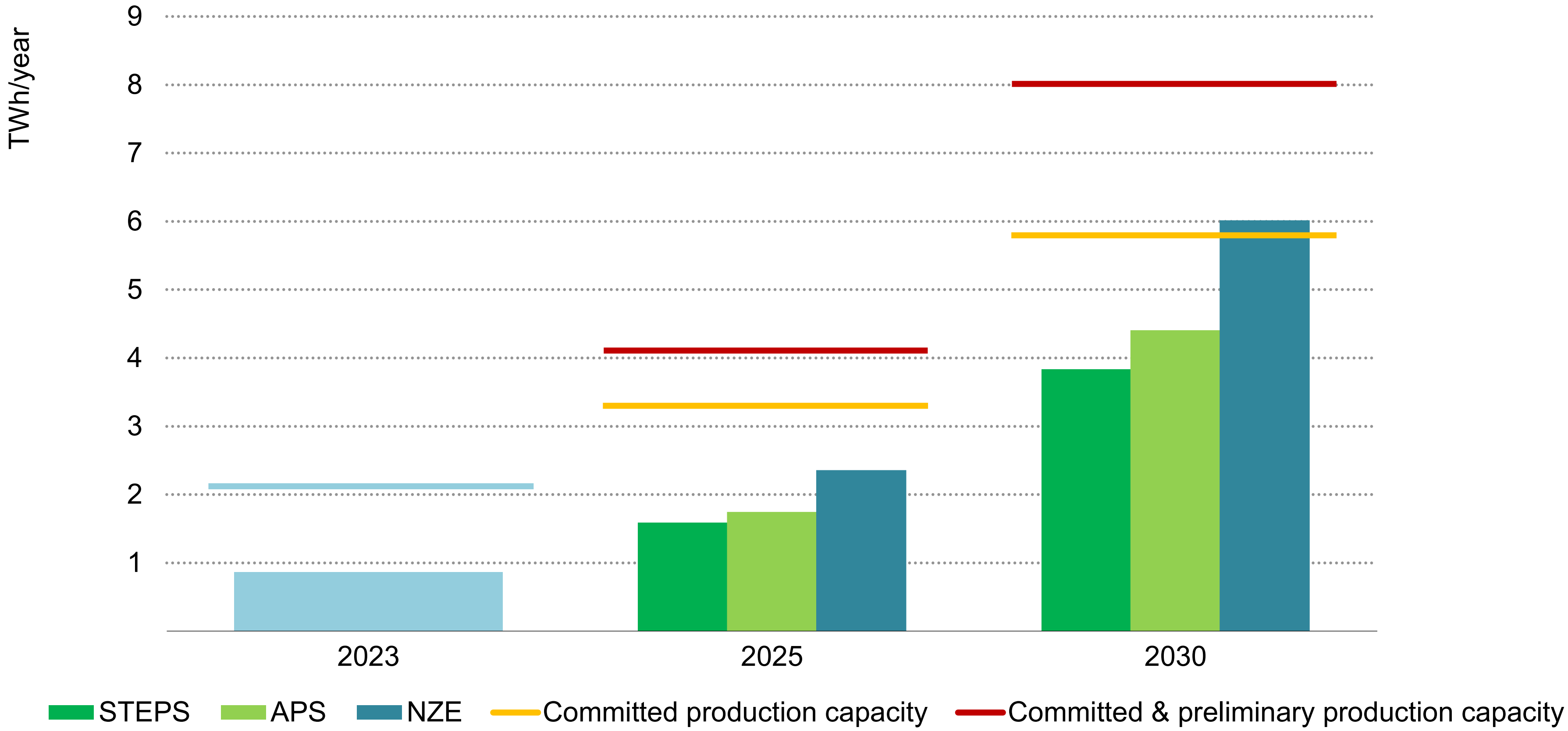
EV sales and battery demand growth by scenario



Notes: EV = electric vehicle; LDV = light-duty vehicle. EV sales numbers exclude two-/three-wheelers. EV battery demand in the NZE Scenario includes all modes.

Manufacturing capacity for batteries is already running ahead of projected demand

Battery production capacity versus demand for both EVs and storage

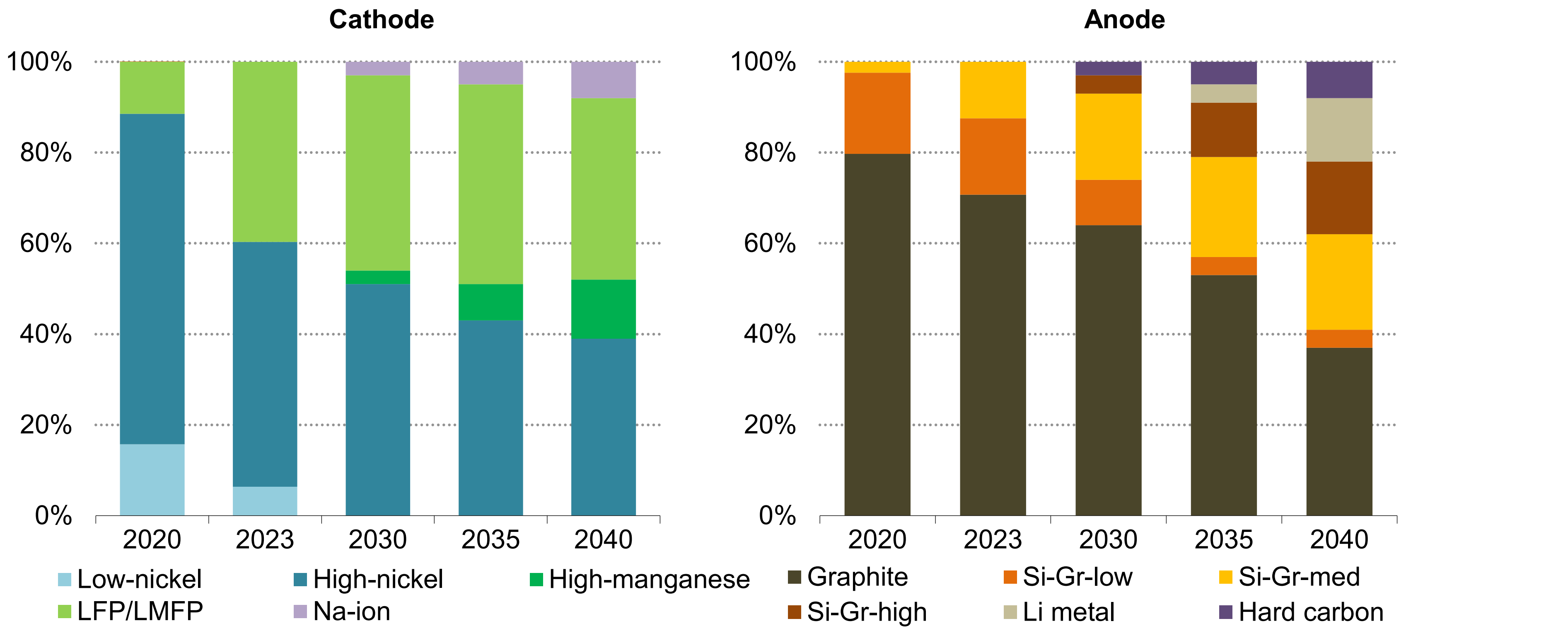


Notes: Demand and capacity include both EVs and storage. Committed refers to current capacity and gigafactories that have reached a final investment decision and are starting or have already started construction, and preliminary refers to gigafactories that have been announced but are not yet being built. Preliminary and committed production capacity assumes a utilisation rate of 85%.

Sources: IEA analysis based on BloombergNEF and Benchmark Mineral Intelligence.

LFP cathodes continue growing in share, and manganese-rich chemistries are set to play a bigger role, while silicon doping of graphite anodes increases significantly

Electric car battery chemistry share development



Notes: LFP = lithium iron phosphate; LMFP = lithium manganese iron phosphate; Na-ion = sodium-ion; NMC = lithium nickel manganese cobalt oxide. NCA = lithium nickel cobalt aluminium oxide. NMCA = lithium nickel manganese cobalt aluminium oxide. LNO = lithium nickel oxide. Low-nickel includes: NMC333 and NMC532. High-nickel includes: NMC622, NMC721, NMC811, NCA, NMCA, LNO. High-manganese includes lithium nickel manganese oxide (LNMO) and lithium-manganese-rich NMC (LMR-NMC). Si-Gr = silicon-doped graphite. Si-Gr-low refers to 5% silicon content, Si-Gr-med = 5-50% and Si-Gr-high > 50%.

The adoption of EVs and battery storage is set to accelerate rapidly over the coming decades, driving a fourteen-fold increase in battery demand by 2050 in the APS

With ongoing policy support, improving economics, and an expanding number of models available, global EV sales (excluding two-/three-wheelers) are set to grow strongly, more than tripling by 2030 in the STEPS and APS to almost 45 million and 50 million vehicles, respectively, and increasing more than fivefold to 70 million in the NZE Scenario. This is primarily driven by the sales of electric cars, where a global sales share of 18% in 2023 increases to 45% in the STEPS and almost 50% in the APS by 2030, while reaching two-thirds of all sales in the NZE Scenario. This rapid sales growth continues to accelerate to 2050 with sales growing more than fivefold in the STEPS and over sevenfold in the APS. Sales grow almost eightfold in the NZE Scenario by 2050 reaching 110 million vehicles. The share of electric cars in total car sales continues to surge, reaching 60% in the STEPS, over three-quarters in the APS and over 95% in the NZE Scenario by 2050.

This exceptional growth in EV sales drives a dramatic growth in battery demand. From almost 1 TWh in 2023, demand more than quadruples by 2030 in the STEPS to 3.8 TWh and reaches 4.4 TWh in the APS, while increasing sevenfold to 6 TWh by 2030 in the NZE Scenario. The growth rates in battery demand outpace growth in EV sales due to additional demand growth of battery storage, which surpasses the rates of demand growth for light-duty vehicles in both the STEPS and APS by 2030 and by 2050. There is also significant growth in battery demand for electric trucks, which increases eighteen-fold in the STEPS and twenty-three-fold in the APS by 2030. In the NZE Scenario, EV battery demand grows sevenfold. By 2050 global battery demand reaches 9 TWh in the STEPS and 12 TWh in the APS, growing tenfold and fourteen-fold from 2023 demand, respectively. In the APS, demand from electric trucks becomes larger than global storage demand in 2050. In the NZE Scenario demand reaches 13 TWh, a fifteen-fold increase.

Manufacturing capacity

In 2023 battery production capacity (at 85% utilisation rates) is two and half times battery demand. Looking forward, our analysis of committed production capacity includes gigafactories that are starting or under construction or have reached final investment decision. In 2025 committed production is double both STEPS and APS demand, while being 40% higher than demand in the NZE Scenario. By 2030, rapid demand growth narrows this gap, such that committed production is only 30% higher than APS demand and close to the requirements in the NZE Scenario. However, if preliminary announcements are included, meaning gigafactories that have been announced but not yet reached final investment decision, anticipated manufacturing capacity takes another leap ahead. When preliminary announcements are included, production capacity exceeds APS demand by 80% and is 40% greater than demand in the NZE Scenario. Of all new committed capacity additions from 2023, 55% are in China by 2030. These projections imply intense price competition among producers, with significant implications for global battery supply chains.

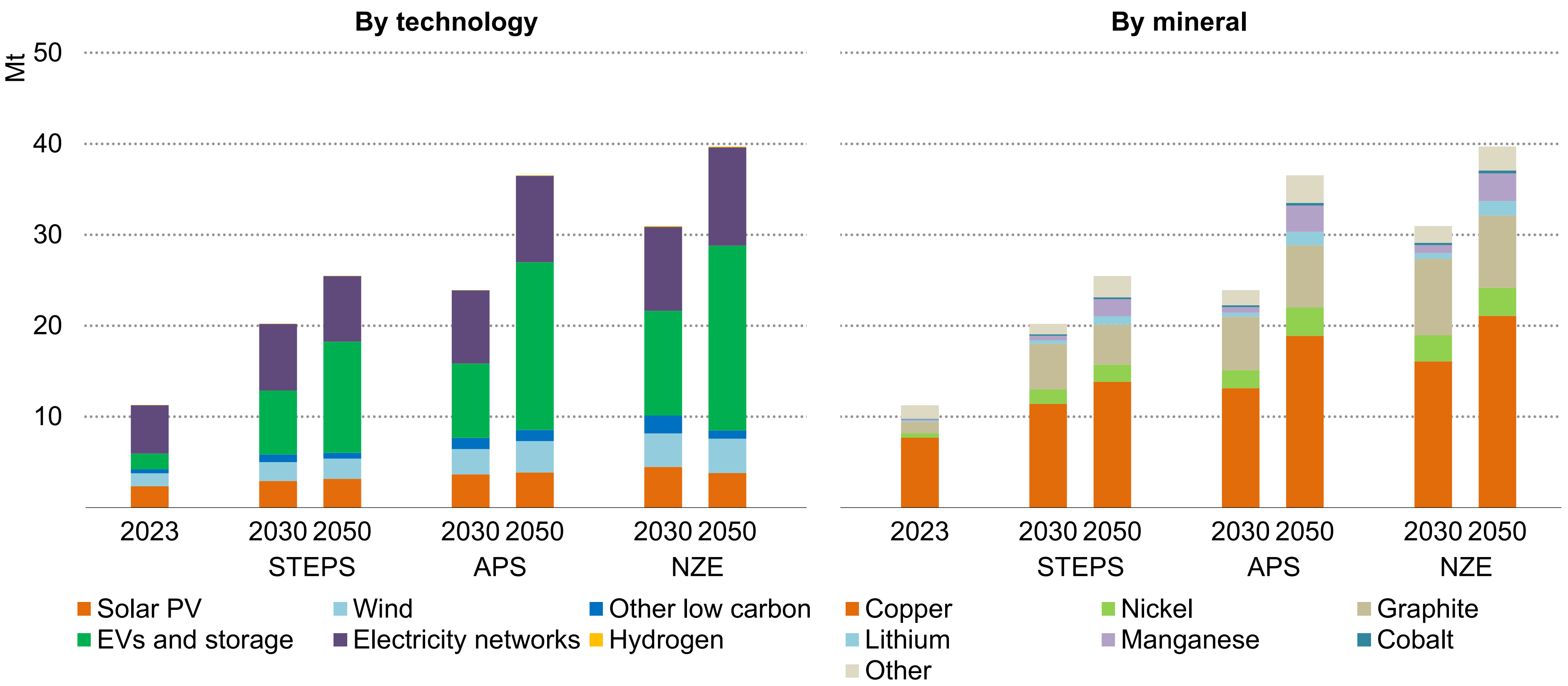
Chemistry development

In terms of electric car cathode chemistries, lithium iron phosphate (LFP) and lithium manganese iron phosphate (LMFP) are set to become the leading chemistries by share from 2035. The LFP variant LMFP looks likely to be increasingly utilised, taking share from LFP and also from the high-nickel chemistries due to its higher energy density than conventional LFP. Low-nickel high-cobalt chemistries such as the nickel manganese cobalt (NMC) 333 are assumed to be phased out by 2030, with the trend of reducing cobalt content in favour of higher nickel contents continuing. Manganese-rich chemistries including lithium-manganese-rich NMC (LMR-NMC) and lithium nickel manganese oxide (LNMO) start to take increasing shares of the high-nickel and LFP market. LNMO are anticipated to take a small share of the mid-range market, being higher energy density than LFP but not near the levels of the high-nickel chemistries. LMR-NMC enables significantly higher energy densities due to its ability to store higher concentrations of lithium, and therefore is expected to take increasing shares of the long-range high-energy-density market at the expense of high-nickel chemistries. High-nickel chemistries continue to play a major role in the long-range market with higher nickel contents being utilised including the 96% Ni NMC. However, their share of the EV market is expected to decrease from 55% in 2023 to around 40% in 2040, as manganese-rich chemistries and LFP/LMFP continue to displace them. This is a remarkable change from 2020 when high-nickel chemistries dominated the EV battery market. Finally, sodium-ion batteries are anticipated to play an increasingly significant role after 2030, reaching a global market share of almost 10% in 2040, displacing some LFP in the low-range EV market, particularly if lithium prices rise and if there are phosphorous supply issues for LFP. Our analysis suggest that LFP remains the preferred solution for the battery storage market, with a growing longer-term role for sodium-ion.

Looking at anodes, current trends indicate a growing share of silicon-doped graphite anodes and a shift towards higher silicon contents. This trend continues to displace conventional graphite anodes, eventually reaching high silicon contents above 50% and ultimately silicon anodes for long-range premium markets. Lithium metal anodes are anticipated to eventually play a greater role after 2035 with ASSBs, hybrid liquid-solid-state batteries and advanced liquid electrolytes, starting with the most premium long-range vehicles. However, the speed of deployment is highly uncertain and dependent on considerable technical and scaling challenges to be solved. Finally, with the increasing adoption of sodium-ion batteries, hard carbon, anode material for sodium-ion batteries takes a greater share of the electric car anode market.

Mineral demand for clean energy technologies doubles between today and 2030 in the STEPS and APS and grows by almost three times in the NZE Scenario

Mineral requirements for clean energy technologies by scenario



Note: Includes most of the minerals used in various clean energy technologies but does not include steel and aluminium.

The energy transition continues to drive mineral demand in all scenarios

The accelerating pace of energy transitions is set to significantly boost mineral demand across all the three scenarios. In the STEPS, demand doubles to 2030 with continued growth thereafter. In the APS, demand more than doubles by 2030 and triples by 2050. In the NZE Scenario, the swifter adoption of clean energy technologies implies an even more pronounced surge in demand for critical minerals, nearly tripling by 2030 and growing to over 3.5 times the current levels by 2050, reaching nearly 40 Mt.

Our latest mineral demand projections have been updated from those in the Critical Minerals Market Review 2023, reflecting several new technological and policy developments:

- Projected demand in the STEPS has been revised upwards due to faster clean energy deployments, notably in solar PV installations and EV sales, driven by strengthened policy measures and improved economics for these technologies.
- Although they face some short-term headwinds, EV sales have also been revised slightly upwards in the long-term, driven by improving economics and policy efforts in major markets.
- LFP shares have increased considerably over the last years, and its rapidly growing global share has been reflected in the updated chemistry projections. Manganese-based chemistries also take a larger share in the future in the revised assumptions. Alongside assessments of other emerging technologies such as sodium-ion batteries, solid-state batteries and silicon-based anodes, near- and long-term battery chemistry assumptions have been adjusted, affecting demand projections for nickel, cobalt, manganese, and other materials.
- The projected deployment of battery storage has been revised upward to account for the rapid pace of deployment in recent years and the increasing need for power system flexibility, resulting in increased demand for battery metals, lithium in particular.
- Material intensity assumptions have been updated based on the latest literature review and industry consultations.
- Graphite material requirements have been revised upwards in all scenarios, reflecting a more detailed representation of the amount of silicon required in anodes.

Each factor influences projected mineral requirements differently, resulting in slightly higher aggregated mineral demand across all three scenarios by 2050 compared with the previous outlook, with the STEPS seeing the largest overall upwards revision.

Demand for each mineral is affected in different ways from these revisions and updates. Nickel sees the largest downwards revisions in both the APS and the NZE Scenario, largely due to the increased prominence of LFP, whereas graphite sees large upwards revisions in all scenarios.

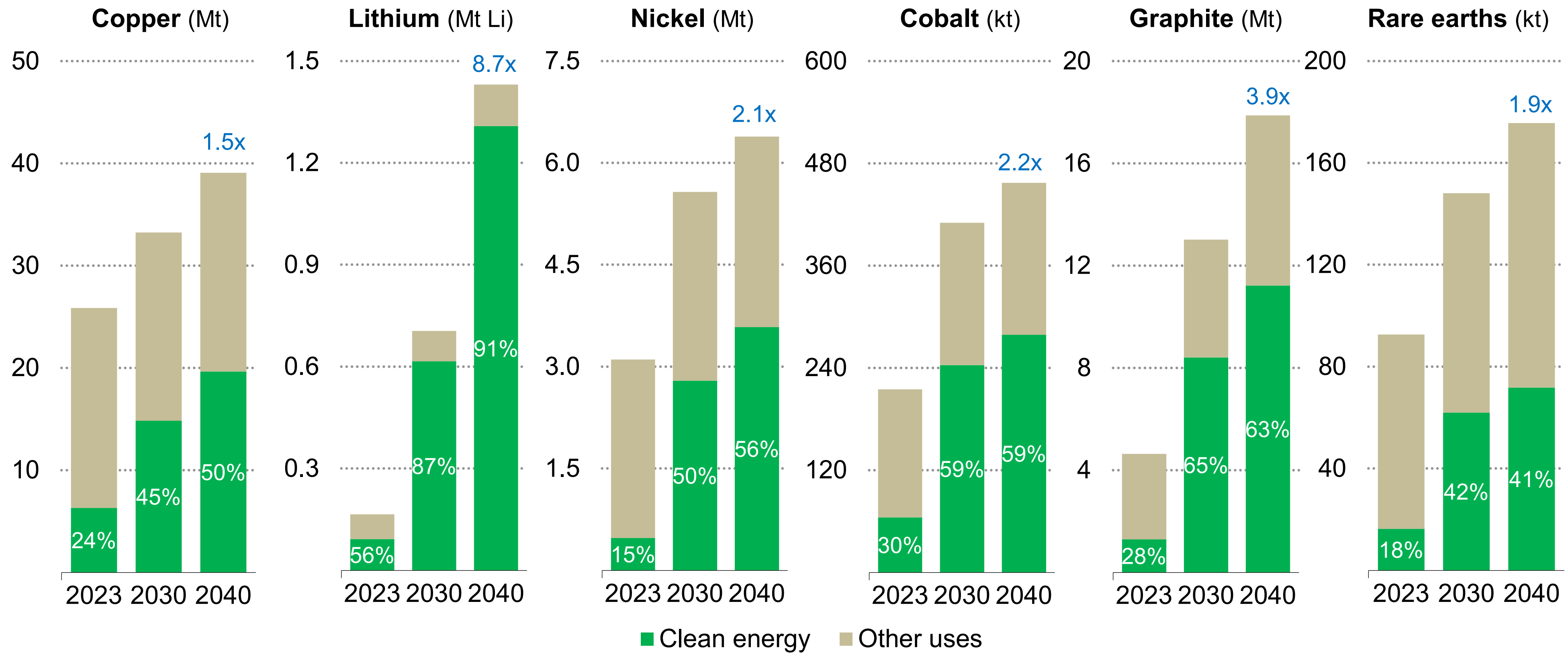
However, despite these adjustments in projected mineral demand, demand in climate-driven scenarios remains multiple times higher than current levels, underscoring the pivotal role of clean energy technologies in propelling total mineral demand growth. From copper to lithium and to cobalt, clean energy technologies emerge as the predominant consuming segment, significantly elevating their share in total demand compared with present levels.

It is important to note that demand projections are subject to large variations, influenced not only by broader policy considerations (reflected in our energy scenarios) but also by technology costs and innovations, as well as behavioural factors. To address this complexity, the IEA has developed more than ten alternative cases to assess the impacts of different consumer preferences and technology advancements on future mineral requirements. The findings of these cases are available through the updated IEA Critical Minerals Data Explorer, an accompanying online data tool designed to allows users to easily access and navigate the projection results (see Annex).

Overview of the projections for key energy transition minerals

Limiting global warming to 1.5 °C, as in the NZE Scenario, means very rapid growth in demand for key minerals

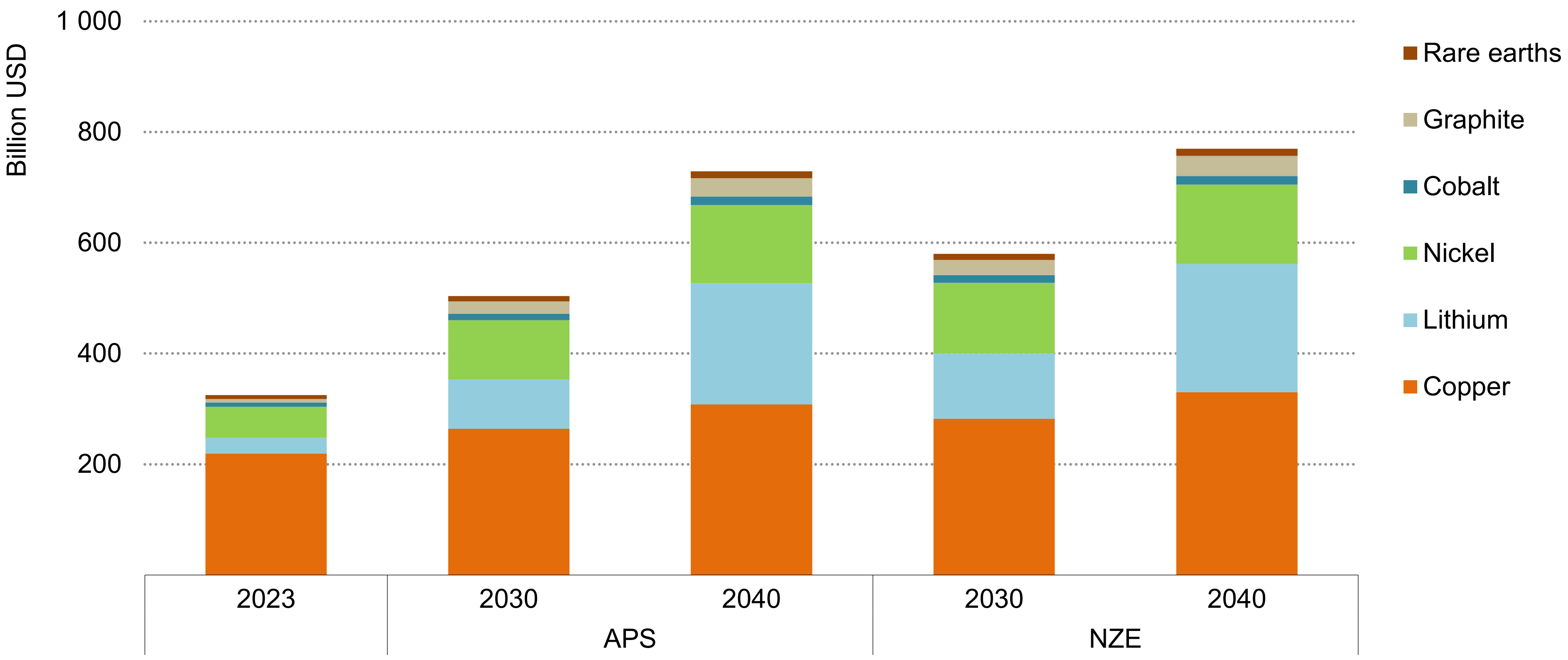
Global critical minerals demand in the NZE Scenario



Notes: The figures for copper are based on refined copper. Those for rare earth elements are for magnet rare earth elements only. Growth rates (in blue) are between 2023 and 2040.

The combined market value of key energy transition minerals more than doubles by 2040 in climate-driven scenarios, reaching USD 770 billion in the NZE Scenario

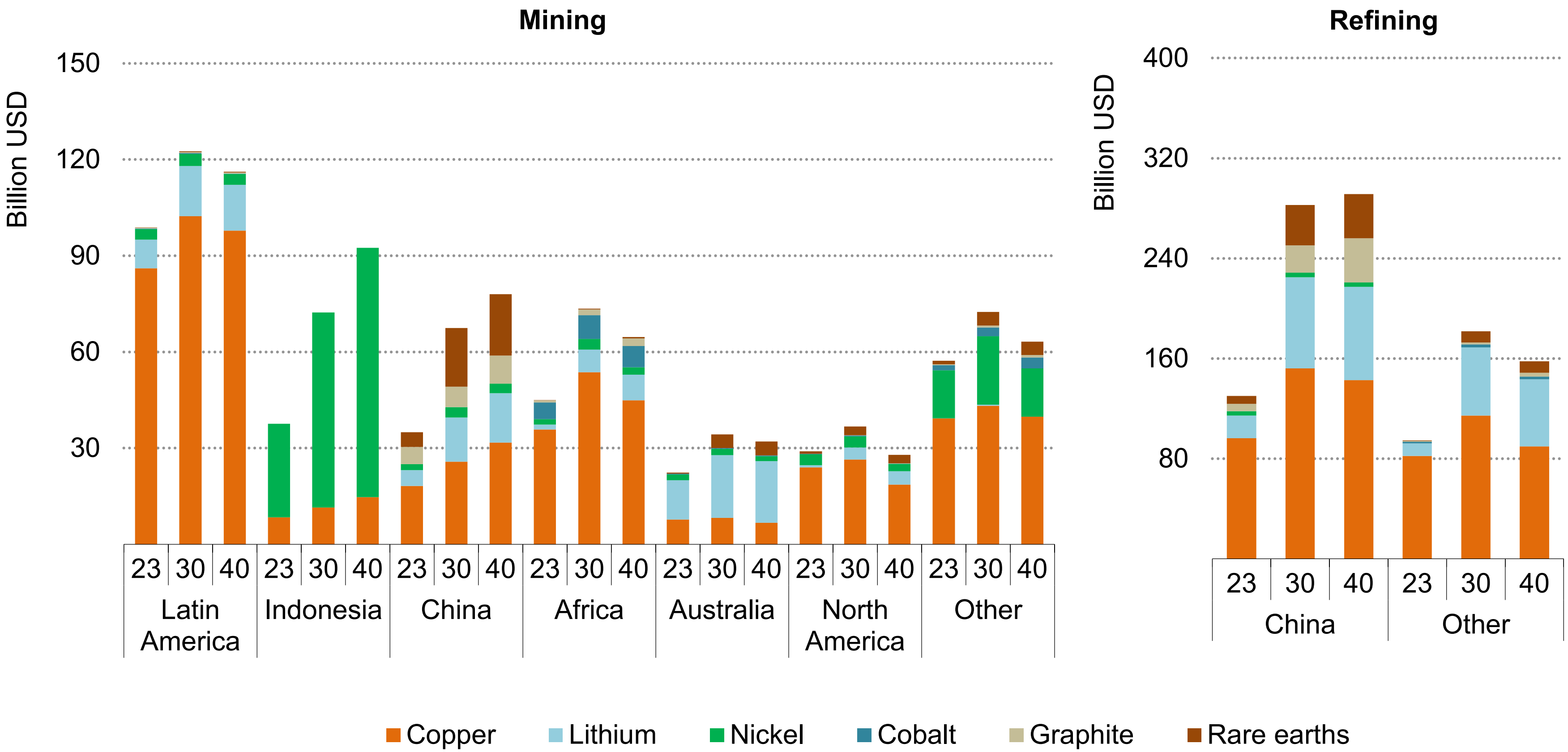
Market value of key energy transition minerals in the APS and the NZE Scenario



Note: 2023 annual average price levels are assumed to estimate the market size for the projection period.

Latin America, Africa and Indonesia see a growing market value from their mining operations; nearly 50% of the market value from refining is concentrated in China by 2030

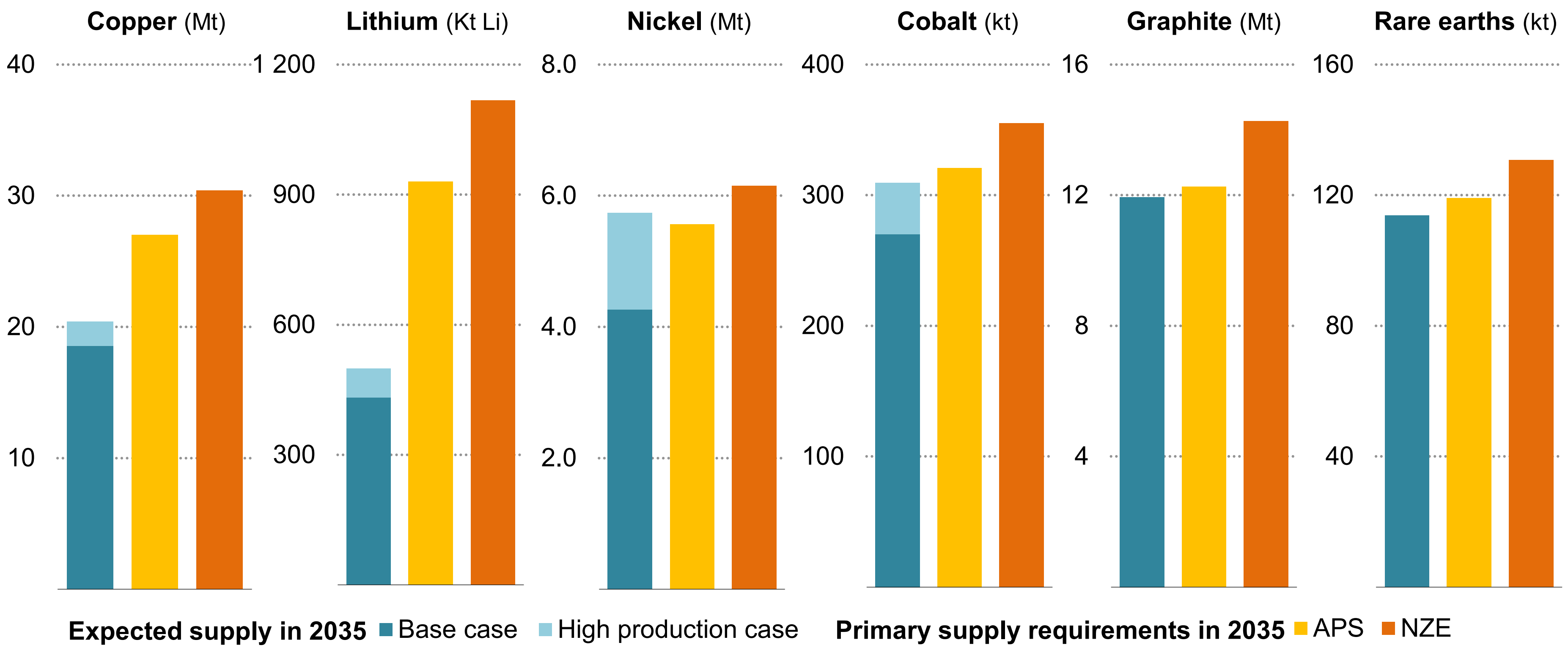
Market value of mined and refined materials in select regions in the base case



Note: Market value was calculated by multiplying each region's production volume in the base case with today's market price for final products.

Expected supply from announced projects is within range of projected 2035 requirements to reach national and global climate goals, with the major exceptions of copper and lithium

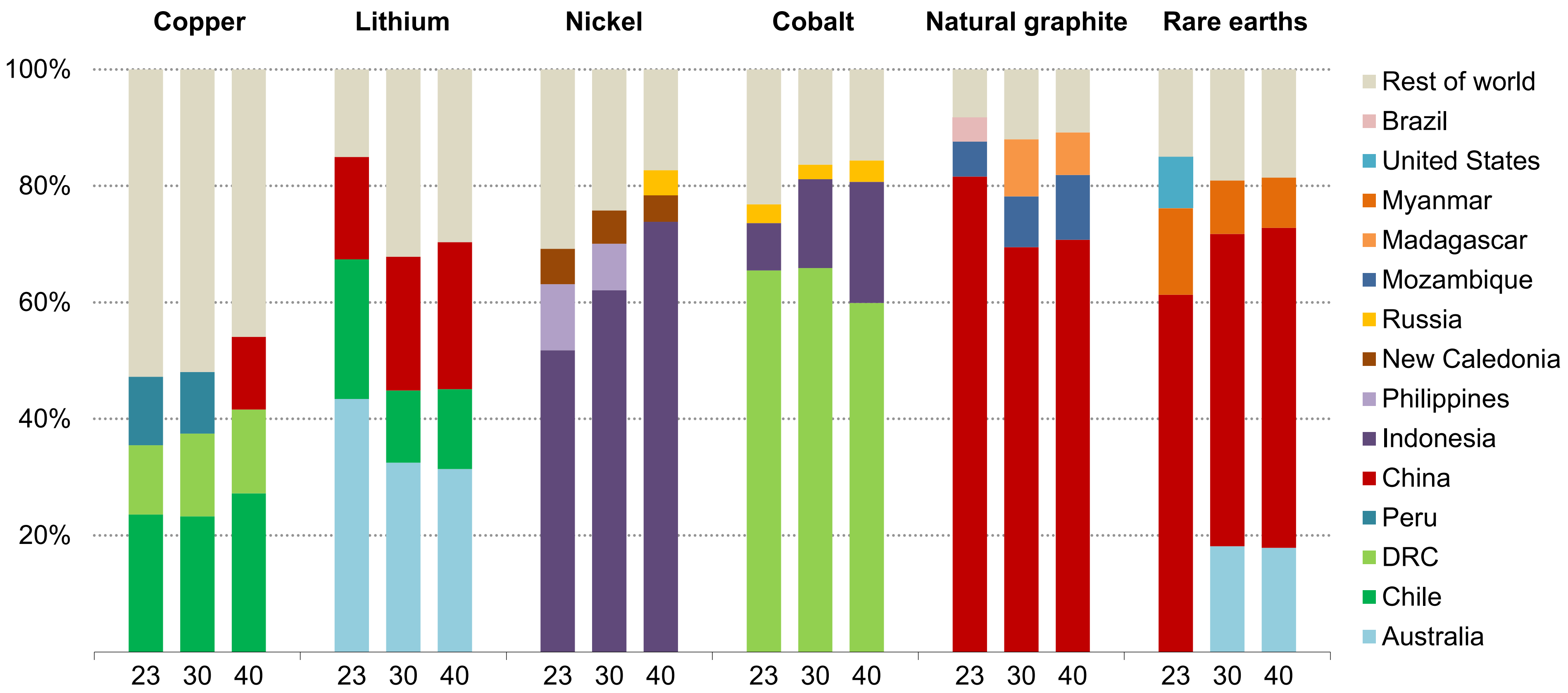
Expected supply from existing and announced projects and 2035 primary supply requirements for focus minerals by scenario



Notes: Expected supply is based on mined or raw material output, except for graphite where the figure includes expected spherical graphite and synthetic graphite supplies. Primary supply requirements are calculated as "total demand net of secondary supply", also accounting for losses during refining operations. The figures for rare earth elements are for magnet rare earth elements only.

Analysis of project pipelines indicates that the geographical concentration of mining operations is set to rise further or remain high over the projection period

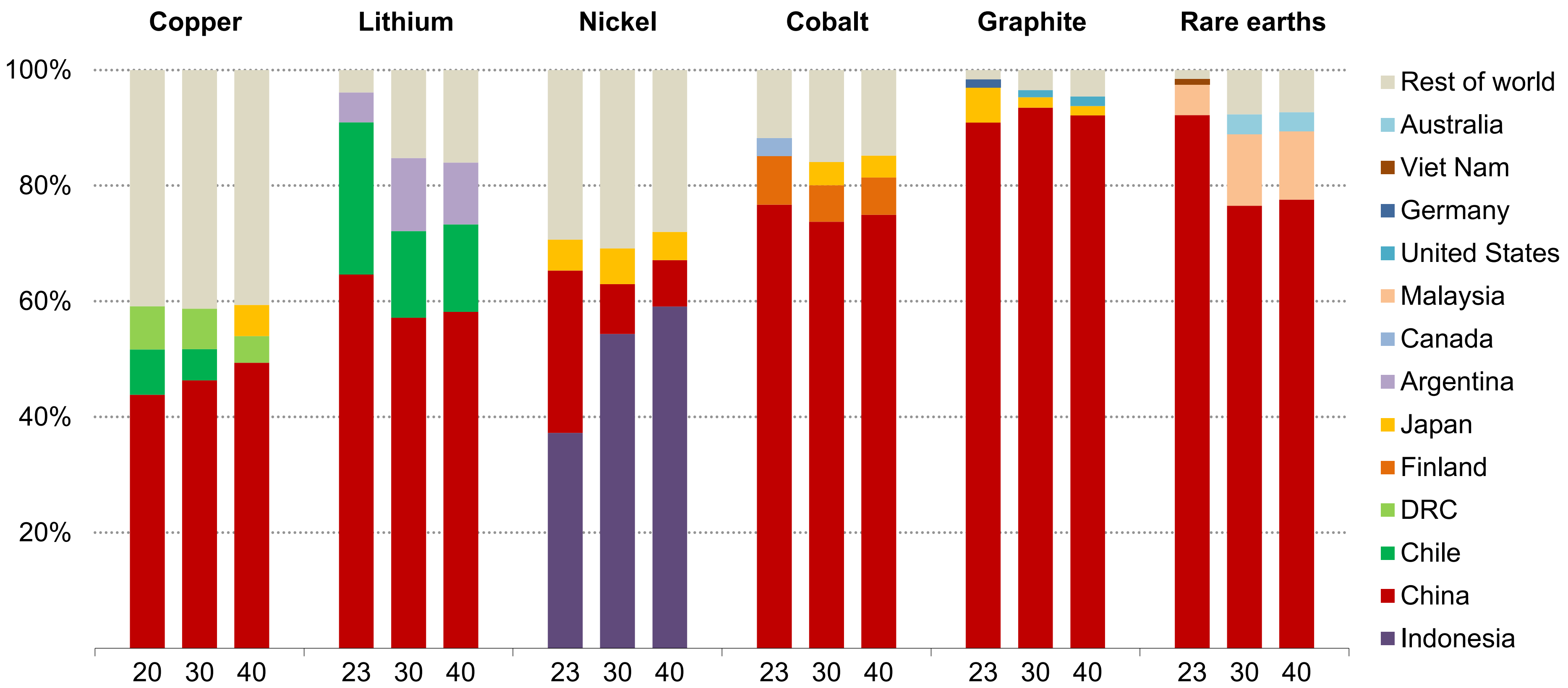
Geographical distribution of mined or raw material production for focus minerals in the base case



Notes: DRC = Democratic Republic of the Congo. Graphite extraction is for natural flake graphite. The figures for rare earth elements are for magnet rare earth elements only. The figure depicts the value of the top three producing countries in a given year.

As many refining projects are being developed in today's dominant producers, refined material production is also set to remain highly concentrated in a few countries

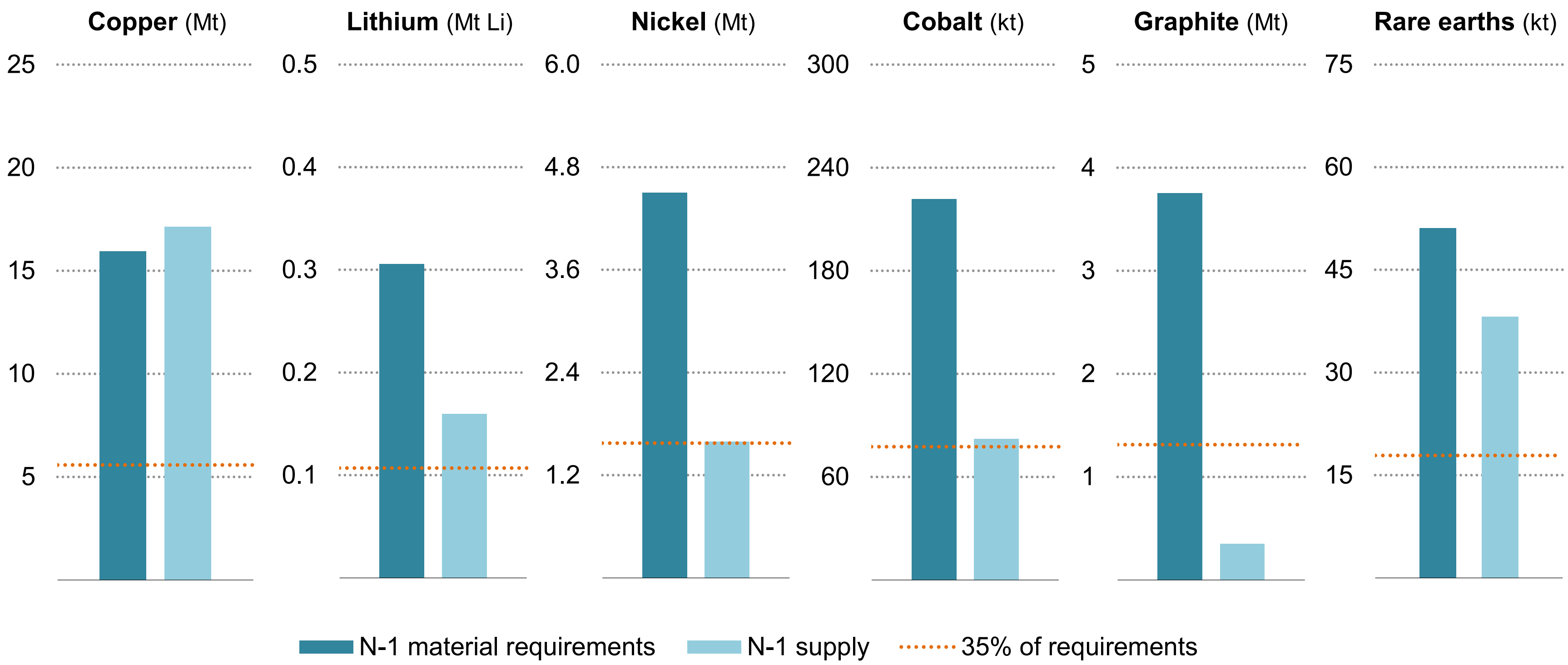
Geographical distribution of refined material production for key minerals



Notes: The figures for graphite are based on battery-grade spherical graphite and synthetic graphite supplies. The figures for rare earth elements are for magnet rare earth elements only. The figure depicts the value of the top three producing countries in a given year.

Major implications for market balances if the largest supplier and their demand is excluded from the equation

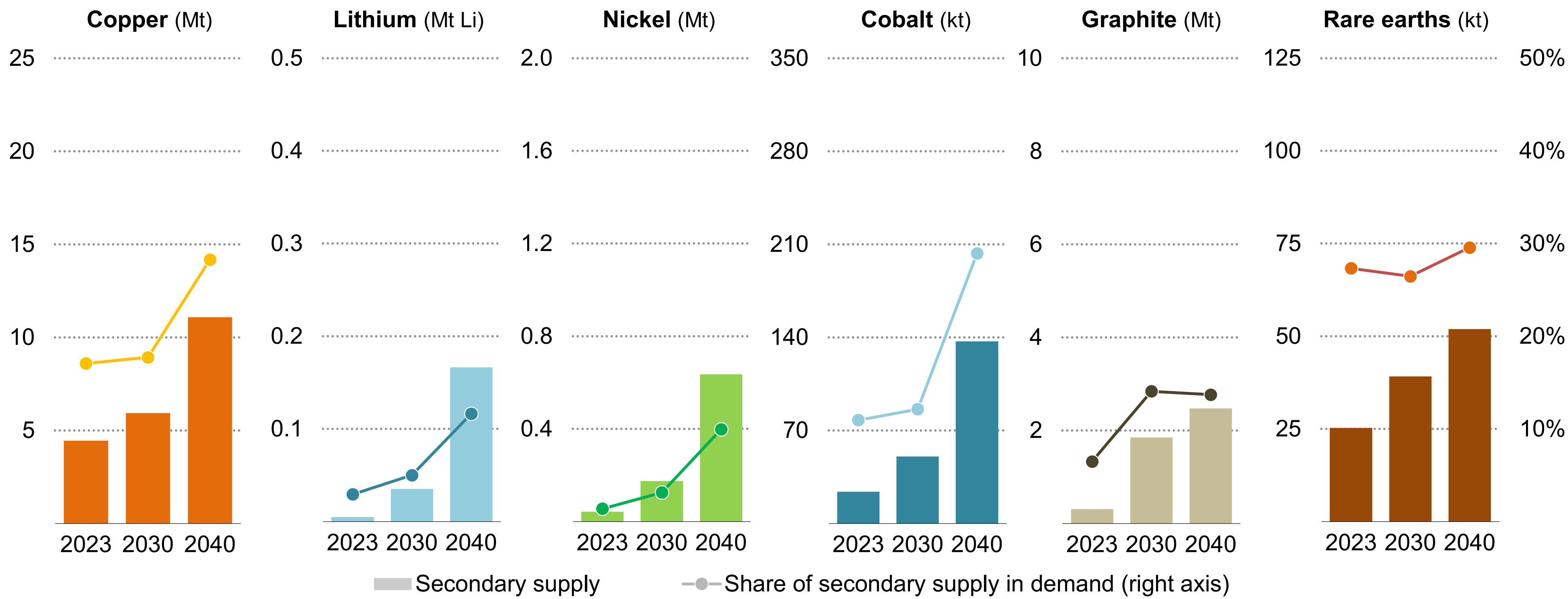
N-1 material requirements and N-1 refined material supply in 2030 in the APS



Notes: The N-1 supply excludes the production volumes from the largest producer from the total global supply, and N-1 requirements exclude consumption of that country from the total global demand. Graphite considers only battery-grade requirements and battery-grade supply, covering both spherical and synthetic materials. The figures for rare earth elements are for magnet rare earth elements only. For demand in the clean energy sector, the N-1 material requirements were estimated by considering each region's share of clean energy deployment. For demand outside the clean energy sector, the region's current consumption share was applied to the projected global demand in 2030.

Secondary supply from recycling plays an increasingly crucial role in meeting demand growth in climate-driven scenarios, particularly after 2030

Secondary supply volumes and share of total demand for focus minerals in the NZE Scenario



Note: Includes recycled volumes from end-of-life equipment and manufacturing scrap. For copper, direct use of scrap is excluded.

A complex and varied picture for future supply-demand balances and security of supply

Demand for key energy transition minerals is set to expand significantly across all scenarios, mainly driven by the burgeoning requirements in the clean energy sector. In the STEPS, demand for lithium grows fivefold between today and 2040, while demand for graphite almost doubles over the same period. Demand for nickel, cobalt and rare earth elements also shows robust growth, increasing by 65-80% by 2040.

If the world gets on track to limit global warming to 1.5 °C, as modelled in the NZE Scenario, demand for copper rises by 50% by 2040. In this scenario, demand for nickel, cobalt and rare earth elements doubles over the next two decades, and graphite demand increases by almost four times to 2040, propelled by the substantial increase in battery deployment for EVs and grid storage. Of all the minerals, lithium stands out in this scenario with nearly ninefold growth by 2040, highlighting its crucial role in batteries. Across all materials, the share of clean energy technologies in total demand rises significantly. In most cases, the clean energy sector emerges as the largest consumer of these minerals. In the NZE Scenario, EVs and battery storage are projected to account for over 90% of total lithium demand by 2030. Moreover, batteries are poised to surpass stainless steel as the leading consumer sector for nickel.

As demand expands, the market value of these minerals experiences substantial growth. From around USD 325 billion today, the combined market value of key energy transition minerals is set to increase by 55% in the APS by 2030 and by 80% in the NZE Scenario. By 2040, the market value more than doubles in climate-driven scenarios, reaching USD 770 billion in the NZE Scenario. In this scenario, copper maintains the largest market value at USD 330 billion, while the lithium market undergoes significant expansion to USD 230 billion by 2040, emerging as the second-largest market, followed by nickel. The graphite market also registers almost sixfold growth over the same period. Today's aggregate market value of key energy transition minerals aligns broadly with that of iron ore. In the NZE Scenario, copper on its own attains that scale by 2040.

In the base case supply scenario, this growth in market value is spread across key regions. For mining, Latin America captures the largest amount with around USD 120 billion by 2030, driven by substantial copper production in the area. Indonesia sees the fastest growth, doubling its market value by 2030 due to its burgeoning nickel mining activities. Africa also witnesses a 65% increase in market value, attributed to the rapid expansion of copper production in the region. However, the market value for refining is notably more concentrated, with China claiming nearly 50% of the market value in 2030. China also sees a rise in market value for mined materials as the country's production of copper, lithium, and rare earth elements undergoes rapid expansion.

The rapidly growing demand for minerals, and the variations seen across different scenarios, raises uncertainties about future market balances, and whether future supplies can match the pace of demand growth in scenarios that meet national and global climate goals.

In recent years, substantial investments have been made in mineral supply, and an increasing number of projects have been announced, indicating an expansion in expected supply volumes in the coming years. In some cases, such as cobalt, nickel and rare earth elements, the expected supply by 2035 from both existing and announced projects look tight, but aligns more closely with the projected demand in the APS, particularly when projects assumed in the high production case come to fruition.

However, the timely delivery of planned projects is far from guaranteed and meeting the requirements in the NZE Scenario necessitates further project developments. A similar trend is observed for graphite, but it should be noted that there is a massive number of announced synthetic anode material projects, primarily located in China. Should natural graphite supply face price spikes or supply constraints, these facilities could offer additional volumes to the supply pool (see "Outlook for graphite").

The situation differs for copper and lithium. Announced projects indicate that a mined copper supply gap may develop in the current decade in the base case. Even under the high production scenario, the anticipated supply by 2035 falls well short of meeting the APS requirements, indicating a potential necessity for a further increase in scrap utilisation, demand reduction through material substitution or technological innovation, alongside efforts to foster additional project developments. Lithium presents another significant challenge, exhibiting a sizeable anticipated gap with climate-driven needs, owing to the strong position of lithium-ion batteries in EVs and storage applications. The current downturn in prices may dampen investment appetite for new greenfield projects, which could have profound longer-term implications.

Global mineral supply chains are not well diversified, as highlighted in Chapter 1, and recent progress on diversifying supply sources has been limited. Will this picture change with the multitude of newly announced projects in recent years? Our analysis of project pipelines suggests that the geographical concentration of mining operations is set to remain high in most cases. The situation improves somewhat in the high production case, indicating that many projects being developed in geographically diverse regions are not among the front-runners for development. This pattern mirrors the situation in refining operations, as most refining projects are located in today's dominant producers, thus prolonging high concentration levels in refined material production. Between now and 2030, some 70-75% of projected supply growth for refined lithium, nickel, cobalt and rare earth elements, and almost 95% for battery-grade spherical and synthetic graphite, comes from today's top three producers. These high levels of supply concentration raise risks of potential supply disruptions due to physical accidents, geopolitical events or other developments in a key producing country, with major potential implications for the speed of energy transitions.

Global demand and supply balances often mask significant regional disparities. From the Inflation Reduction Act (IRA) in the United States (US) to the European Union's (EU) Critical Raw Materials Act (CRMA), a wave of policies is emerging aimed at diversifying sources of supply. The IRA seeks to restrict the utilisation of materials obtained from Foreign Entities of Concern, while the EU CRMA targets that no single country should supply more than 65% of Europe's annual consumption of any key materials (implying that at least 35% should come from non-dominant players). Other major consuming countries are increasingly aligned with the objective to diversify their supply sources.

However, given that the top producing nation is responsible for a large portion of global supply for most minerals, available supply outside the largest producing country may be significantly constrained to achieve these ambitions. We conducted the "N-1 test" to assess how the supply and demand landscape might appear if the largest global supplier were removed from the market. Specifically we assessed N-1 supply and N-1 material requirements in 2030 in the APS, excluding both anticipated supply from the largest supplier and projected demand from that country. In most cases, the N-1 supply falls significantly below the N-1 material requirements (even for minerals where the overall global balance is reasonably well supplied). If the CRMA's non-single-origin minimum threshold (35%) is applied in a global context, the N-1 nickel and cobalt supply is barely able to meet this minimum threshold. The situation is even more pronounced for graphite. Although there is abundant supply of graphite globally, the expected N-1 supply is entirely insufficient to meet the minimum threshold. This indicates that without efforts to develop additional projects in geographically diverse regions, achieving the goals set by policy legislation would be challenging.

This analysis underscores the need for concerted efforts to expedite the development of promising projects located in geographically diverse regions. Additionally, it highlights the importance of harnessing the potential for value chain expansion in major resource holders in emerging and developing economies, provided such expansion is economically viable and can yield significant economic and social advantages.

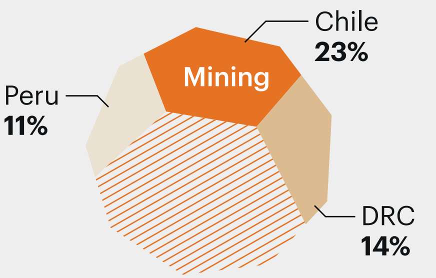
Investment across the supply chain is crucial, yet equally vital is unlocking the potential of recycling, innovation, and behavioural change. A strong emphasis on recycling can not only diminish the magnitude of primary mineral requirements but also yield substantial security benefits for regions dependent on imported materials. While the share of secondary supply from recycling in total demand remains modest for most focus minerals, it experiences significant growth in the NZE Scenario, particularly post-2030, as policy mandates strengthen and a substantial volume of end-of-life EV batteries enters the market (see Chapter 4, "Recycling, innovation and behavioural change" section).

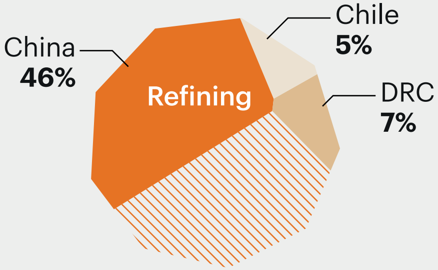
Outlook for copper

Copper

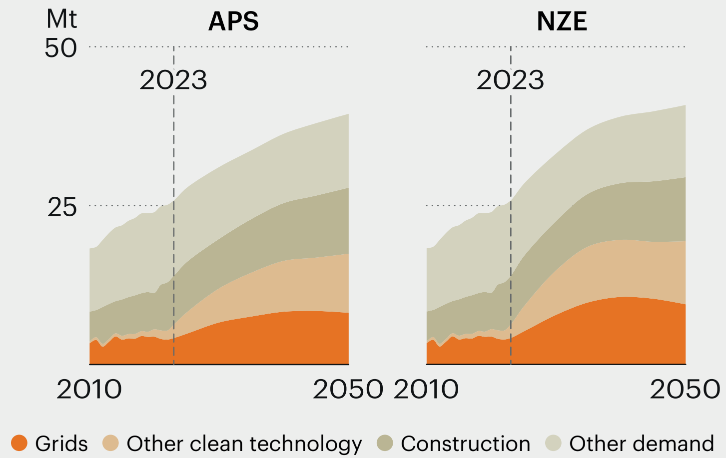
Cu

Top three producers 2030

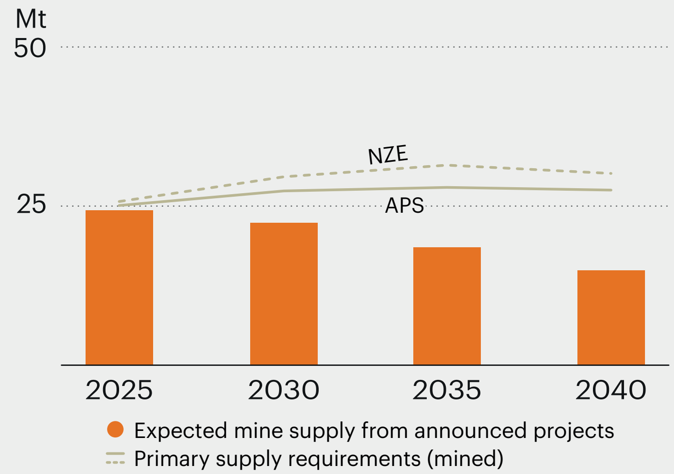




Demand outlook



Mining requirements



Milestones (APS)	2021	2023	2030	2040
Cleantech demand (kt)	**5 380**	**6 311**	**12 001**	**16 343**
Other uses (kt)	19 548	19 543	19 127	20 036
Total demand (kt)	**24 928**	**25 855**	**31 128**	**36 379**
Secondary supply and reuse (kt)	4 123	4 445	5 879	11 006
Primary supply requirements (kt)	**20 805**	**21 409**	**25 249**	**25 373**
Share of top three mining countries	46%	47%	48%	54%
Share of top three refining countries	57%	59%	59%	59%

Clean energy transition risk assessment

Low Med High

Supply risks

31%

shortfall in project pipeline vs. 2035 APS mining requirements

Geopolitical risks

Relatively

diversified

supply sources

Barriers to responding to supply disruption

Mature markets

with sizeable volumes of secondary supply

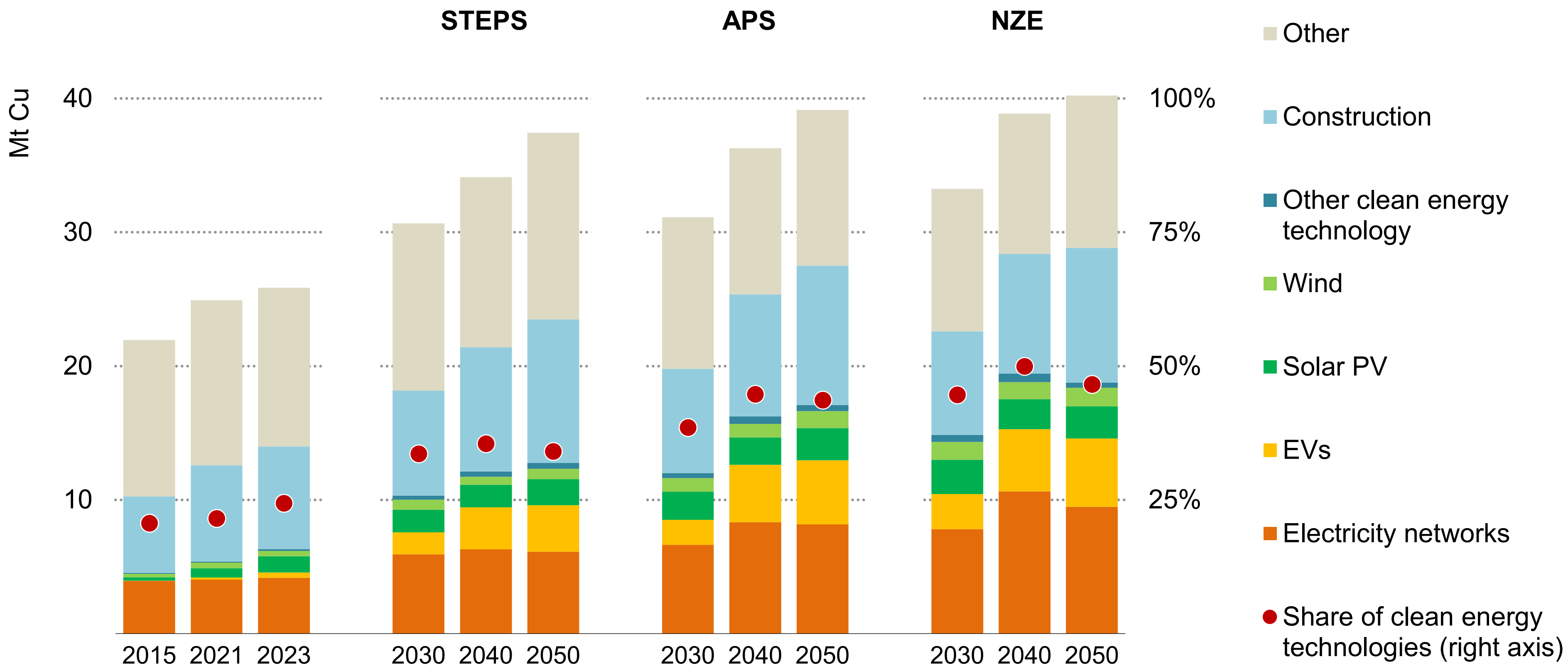
ESG and climate risk exposure

52%

of mines located in high water stress areas

Demand: Clean energy technologies drive substantial growth in copper demand

Copper demand outlook by sector and scenario



Notes: Copper refined demand excluding direct use scrap. EVs demand includes both EV batteries and EV motors demand. Other demand includes: Industrial equipment, other transport, consumer products, cooling, communications, and other electronics.

Demand: Copper demand grows rapidly in all scenarios, driven by the rapid deployment of renewables and EVs

Copper is the only critical mineral present in all of the most important clean energy technologies – EVs, solar PV, wind, and electricity networks – due to its unmatched combination of characteristics: electronic conductivity, longevity, ductility and corrosion resistance. Therefore, the security of supply of copper is paramount for the energy transition. Total copper demand is made up of a combination of refined copper demand (including both primary and secondary production, 26 Mt in 2023) plus direct use of scrap (over 6 Mt).

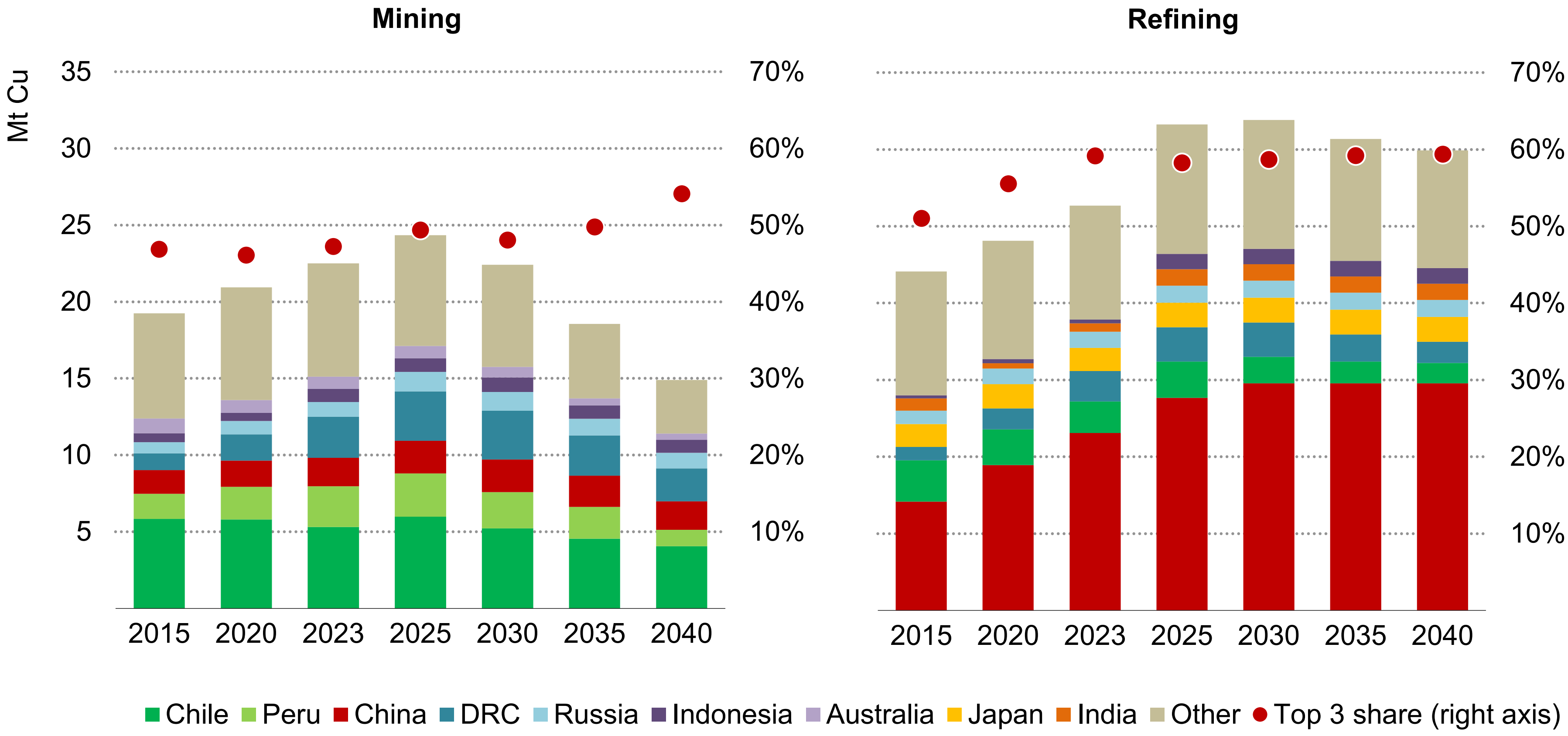
Historically, refined copper demand has been dominated by construction and electricity networks, responsible for 30% and 15% of global demand in 2023, respectively. Other key sources of demand include industrial machinery and equipment (12% of 2023 demand) and the transportation sector (15% of 2023 demand), as copper is used in the manufacture of key components in all modes of transport.

Global refined copper demand grows from 26 Mt in 2023 to 31 Mt in the STEPS and APS and 33 Mt in 2030 in the NZE Scenario. Demand increases further by 20% through to 2050, reaching around 40 Mt in 2050 in the NZE Scenario. This surge in demand is primarily due to the rapid deployment of renewables and EVs, and a significant expansion of electricity networks. Copper is critical for lithium-ion batteries for EVs, being irreplaceable for the anode current collector, as well as being used in wiring in the battery packs and being a key component of EV motors. Electricity networks remain the second-largest source of demand after construction for the STEPS and APS, but in the NZE Scenario, it becomes the largest source of demand by 2030 before construction again overtakes to be the dominant source after 2040. However, copper demand from EVs experiences the largest growth in demand, increasing more than twelvefold from 2% of demand in 2023 to 12% in 2050 in the APS and 13% in the NZE Scenario. Overall, construction remains the leading source of refined copper demand in climate-driven scenarios although material efficiency measures temper demand in the sector.

The share of clean energy technologies in refined copper demand has grown modestly in recent years from 22% in 2015 to a quarter in 2023; however, this decade the share dramatically increases, reaching a third in STEPS, almost doubling to reach almost 40% in the APS and 45% in the NZE Scenario in 2030 due to the rapid deployment of renewables and EVs. The earlier electrification of end uses and penetration of renewables requires a rapid addition of electricity networks over the period to 2040, after which the pace of expansion decelerates. This leads to a decrease in copper demand for electricity networks between 2040 and 2050, resulting in a slight decrease in the share of clean energy technologies.

Supply: Chile remains the leading copper miner with the DRC the new second, while China continues to dominate copper refining

Copper production from operating and announced projects in the base case



Note: DRC = Democratic Republic of the Congo.

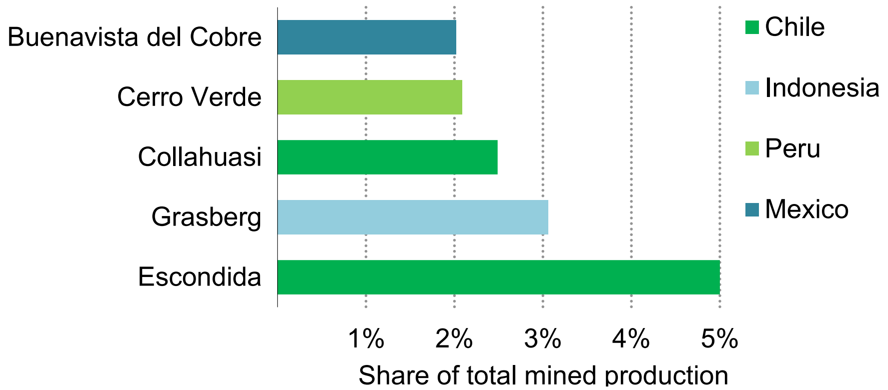
Supply: Lack of large-scale projects in the pipeline poses challenges for future copper supply

Mining

Global mined copper supply reached 22.5 Mt in 2023, up 8% from 2020. Today's copper supply is relatively diversified compared with the other key energy transition minerals. The share of the top three producers was 47% in 2023, and it has been at a similar level since 2015. Chile is the world's current largest producer, producing a quarter of global supply. This is down from 30% in 2015 due to declining ore grades, ageing assets and low reinvestment in expansion. Meanwhile, with its remarkable growth of copper output, the DRC has doubled its share of global supply from 6% to 12% over the same period, overtaking Peru as the second-largest supplier. The DRC copper belt is home to some of the highest-grade copper resources in the world, for instance the Kamoa-Kakula mine is one of the world's highest-grade major copper mines, ten times the global average (5.5% compared with the global average of 0.6%). This makes capital and production costs, and emissions in the DRC significantly lower than other regions, driving a dramatic growth in supply. China is the fourth-largest producer with 8% of global supply while Russia supplies 5%. Indonesia has seen impressive growth since 2020 doubling its share to 5% in a few years while the share of Australian supply has been decreasing. The top three copper mines in 2023 produced over 10% of global copper production, being Escondida in Chile, PT Freeport Indonesia (Grasberg) in Indonesia and Collahuasi in Chile.

Based on the current project pipeline, mined copper supply reaches around 25 Mt in 2026 then declines thereafter as assets age and grades decline. The top three producer's share in total mine production increases to 55% by 2040 from 47% today. Chile remains the largest producer going forward, contributing around a quarter of global supply through to 2040 while the DRC remains the second-largest producer. China also continues to grow its share of global supply, from 8% in 2023 to 12% in 2040. Russia and Indonesia also continue to grow in supply share, together supplying 13% in 2040. The growing share of supply from these countries displaces a significantly shrinking share from Peru, which drops from 12% today to 7% in 2040 due to a lack of viable projects and ageing assets.

Top five largest copper mines 2023



Source: IEA analysis based on Wood Mackenzie.

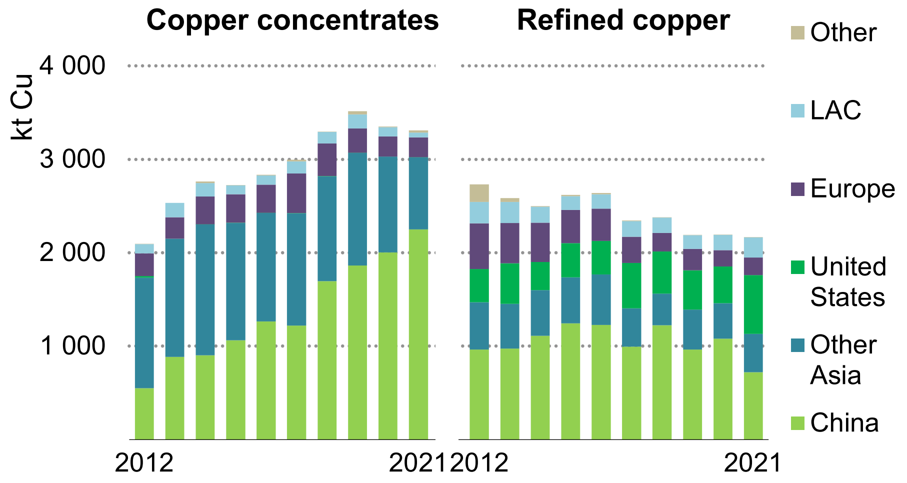
Beyond the challenges of declining copper ore quality, there are additional pressures coming from local social and environmental opposition, particularly in Latin America. At the end of last year, Cobre Panama, one of the largest copper mines in the world supplying 1.5% of global copper output, was shut down by the government due to widespread protests regarding environmental damage and corruption concerns. Beyond the loss of one of the largest copper producing assets, the case is expected to deter mining investment in the country. One of Peru's largest copper mines, Las Bambas, also saw a strike at the end of last year due to workers conditions, having already seen disruptions previously due to indigenous community protests demanding more equitable distribution of mining gains with the local community, as well as other protests. With most of the world's largest mines located in Latin America, if several of these face major opposition, disrupting logistics or shutdowns similar to Cobre Panama, there could be major consequences for global copper supply. The world's largest copper mine Escondida Chile produces 5% of global copper supply alone, while four of today's top five mines are located in the region, emphasising the vulnerability. Efforts to expand mines in other places could reduce this dependency.

Refining

Copper refining is more concentrated than mining, with a current top three refiner share of 60%, becoming more concentrated since 2015. Refining is much more concentrated in a single country. China is currently the world's dominant copper refiner, with 45% market share, having rapidly grown from 30% in 2015. Despite Chile being the world's largest copper miner supplying a quarter of global supply in 2023, it produces only 8% of the world's refined copper, and this share has decreased since 2015 when it was 12%. This demonstrates that over half of Chile's mined copper concentrate is exported for refining, with the majority to China. Copper concentrate is the number one exported product from Chile in terms of value. Since 2012 exports of copper concentrates from Chile have increased 60% mainly to China while exports of refined copper have dropped 20% over the same period. This decline is largely due to the decline in production from solvent extraction electrowinning (SxEw) mines which directly produce refined copper from oxide ore. As the oxide ore supply decreased, with many transitioning from processing oxides to conventional sulphide mining, its export of concentrate increased and refined copper decreased. There are also environmental concerns which have led to the closing of smelters in Chile.

The DRC is now the joint second-largest copper refiner with Chile. While Chile has lost market share since 2015, the DRC has doubled its share in the same time up from 4%. The top three copper refineries in 2023 produced 9% of global refined copper, being Guixi and Jinchuan in China, and Onsan in Korea.

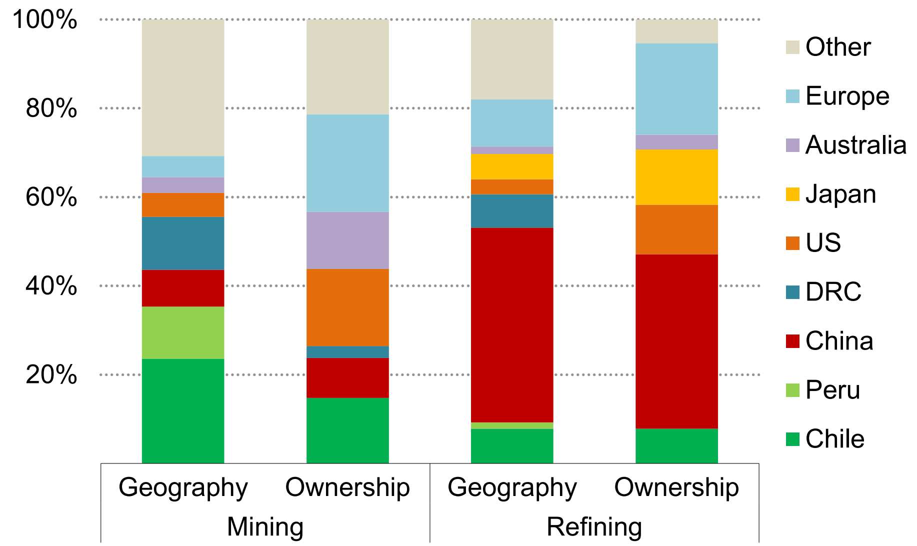
Copper exports by Chile by type and destination



Note: LAC = Latin America.
Source: IEA analysis based on COCHILCO (2023).

Going forward, the share of the top three refiners remains at the same level at around 60%. China, however, continues to increase its dominance of copper processing, supplying around half of global refined copper from 2030 onwards. Little change occurs for the other countries in this period. This again creates a major dependency and vulnerability. Countries in Latin America could prioritise the development of greater domestic processing capability. Not only would this help diversify refined supplies of copper, it would support the countries' economies increasing their share of the value chain. However, cost and environmental concerns are key barriers. Smelting is not a high-margin business, and increasing pressures from high labour and energy costs have made it challenging to compete with China. Capital requirements to reduce emissions and increase the sustainability of operations add to this pressure. Recently Chile's Codelco closed its Ventanas smelter due to pollution which resulted in a poisoning incident in the local community.

Copper mining and refining by geography vs. ownership, 2023



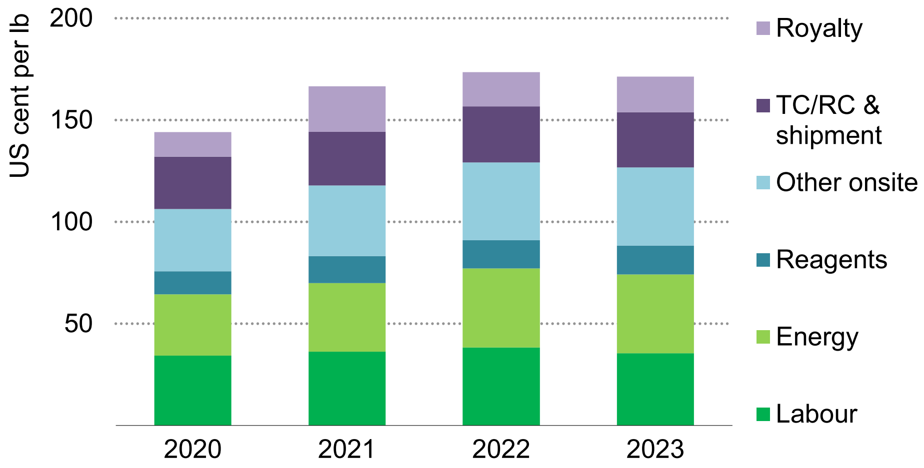
Notes: Ownership analysis of top 20 mining and refining companies in 2023 representing 57% of mined and 56% of refined copper production. Ownership based on headquarters location.
Source: IEA analysis based on Wood Mackenzie.

Looking at mining and refining production in 2023 by ownership (defined based on company headquarters location) shows a different picture from production location. Based on the analysis of top 20 companies, mining appears to be similarly diversified by ownership with a top three country owner share of 45%, the same as production location. European companies are in fact the largest copper producers with over 20% of production. US companies also produce almost 20% of global supply, despite little mining taking place domestically, and this is all from two companies: Freeport-McMoRan and Southern Copper. Companies from Australia and Canada are also major copper producers, together supplying 20% of production despite limited domestic supply. In terms of refining, the picture is similar with Chinese companies dominating with 40% of production. Top three refining countries' share by owner is the same as by location with 60%. European companies are the second-largest refiners with 20% as well as being the second-largest refining location but with only 10% by geography. Japanese companies are the third-largest refiners despite being the fifth-largest refining location. Again US companies play a leading role in copper refining being the fourth-largest refiners.

Capital and operating costs

Declining ore quality is the most critical issue for copper, resulting in increasing capital and operating costs. Operating costs have increased in most areas in real terms since 2020 with energy, on-site, treatment and refining charges (TC/RCs), shipment costs and reagent cost increases all being major drivers. Capital costs have also increased significantly for new copper projects. Recent brownfield projects have a capital intensity around USD 30 000 per tonne, whereas in real terms past brownfield projects initiated around 2017 were cheaper at around USD 20 000/tonne. Expansions are costing more due to having to go deeper and the need to mine more waste to maintain production levels from the declining ore quality. Greenfield projects also suffer higher costs due to the lack of high-quality resources, the need to comply with higher ESG standards, challenging geology, and higher labour and equipment costs. The recently commissioned DRC mine Kamoa-Kakula, with one of the highest-grade copper ore in the world, contrasts from current trends with a capital intensity around just USD 7 000/tonne, demonstrating the major cost advantages in the high-grade areas of the DRC, and explaining its rapid rise in supply.

Operating costs for copper mining (real)



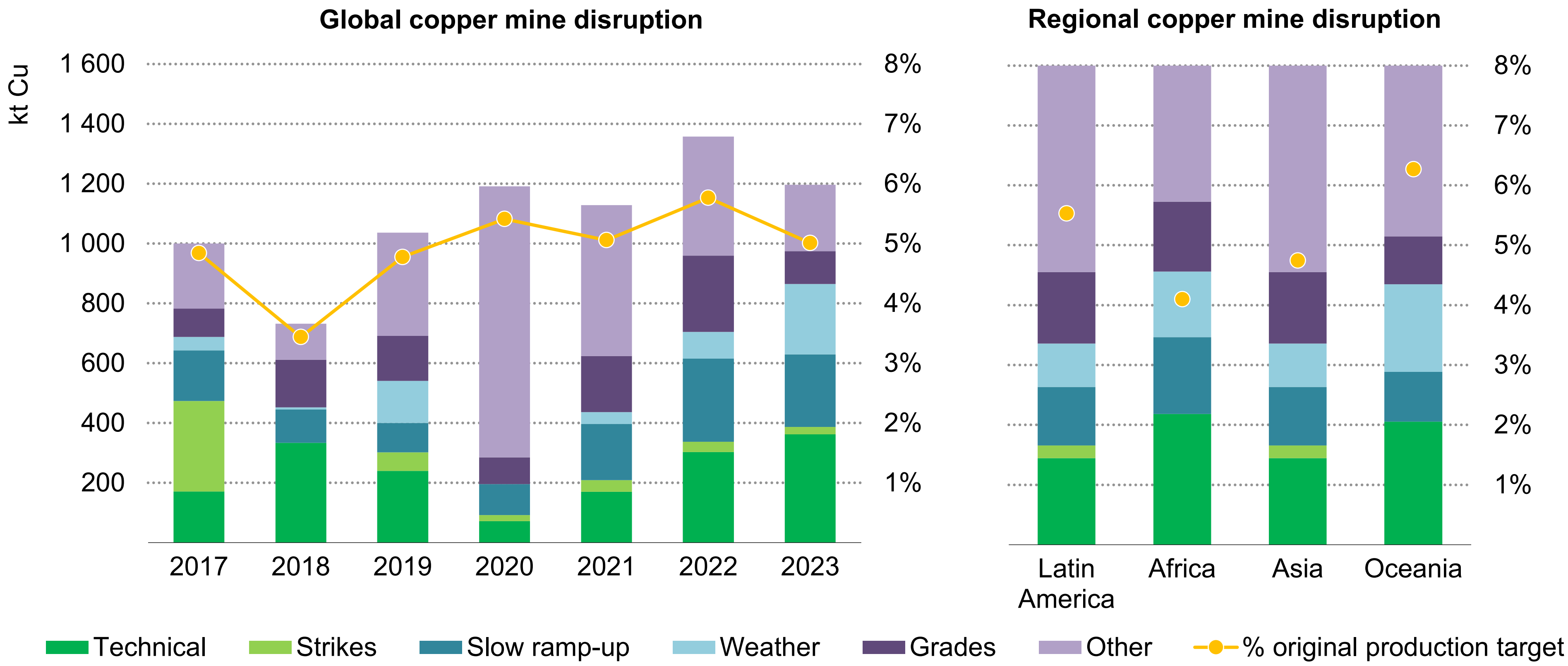
Notes: lb = pound. Companies representing 75% of total copper production.
Source: IEA analysis based on S&P Global.

Copper mining disruptions

Adding to the supply pressures from the declining ore quality are various disruptions to copper supply (assessed as shortfalls relative to expected supply). The global disruption rate in copper supply has been consistent around 5% of the original targeted production. At a global scale, the primary causes vary considerably with the leading causes being technical issues, slow ramp-up, and grades being lower than anticipated. Strikes have been a less critical issue over recent years; however, in 2017 they resulted in exceptional disruption due to strikes at the world's largest mine Escondida in Chile. In 2020, Covid-19 was the primary cause of supply issues. Regionally, the picture varies considerably. Averaged over the past seven years, Oceania (predominantly Australia but including Papua New Guinea) has the highest apparent disruption rate over 6% of anticipated production, while Africa has had the lowest with 4%. However, in both regions technical disruptions are responsible for a higher share of disruption than the global average. Oceania has also been disproportionately affected by weather-related issues.

Supply: Oceania and Latin America suffer greater disruptions to mining supply

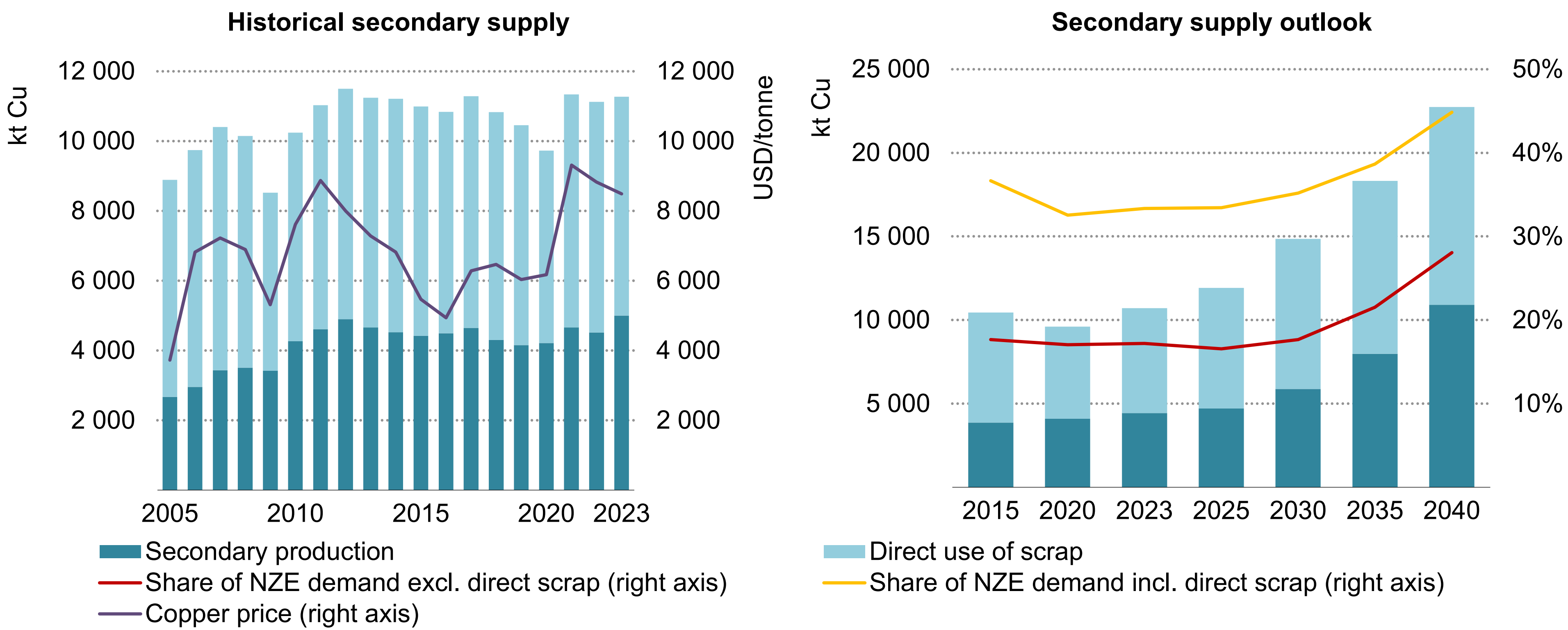
Copper mining disruptions by cause



Note: Regional mine disruption breakdowns are based on the last seven-year average. Oceania includes Australia and Papua New Guinea
Source: IEA analysis based on Wood Mackenzie.

Secondary supply: Copper recycling and direct use of scrap is set to increase substantially from 2030 providing a major source of supply in the future

Historical and projected secondary copper supply in the NZE Scenario



Notes: Direct use of scrap refers to high-grade manufacturing scrap which can be directly used as a source feed. Secondary production refers to end-of life and manufacturing scrap which must be further processed by smelting and/or refining before usage.
Source: IEA analysis based on Wood Mackenzie and S&P Global.

Secondary supply: Copper scrap plays an important role in cushioning potential market tightness or price shocks

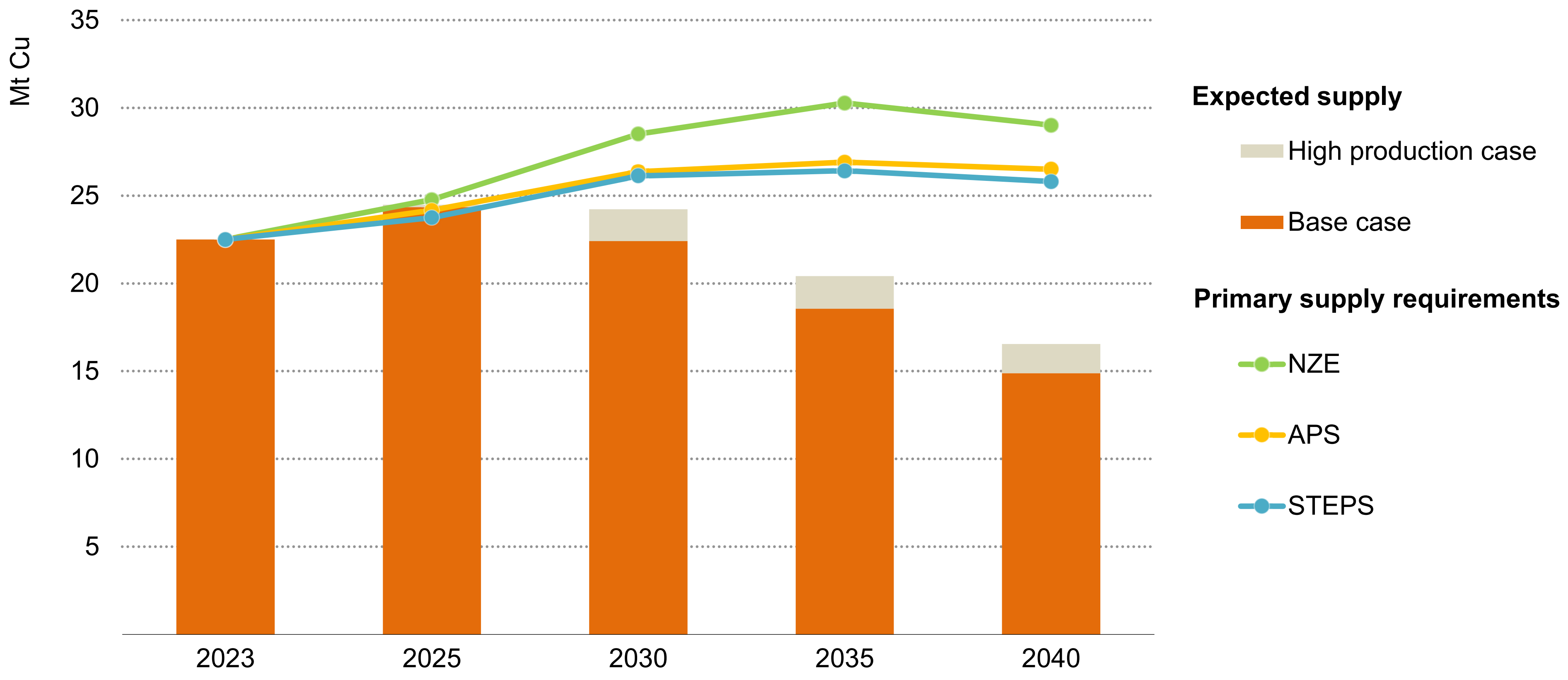
Copper scrap falls under two broad categories. High-grade or No. 1 scrap, known as direct use of scrap, is directly used by semi-manufacturers supplementing their cathode supply as a source feed. There is also lower-grade No. 2 scrap, which contains greater impurities and is used by smelters and refineries. The higher impurities prevent this scrap from being used directly.

Looking at historical secondary supply correlations with copper price shows they are strongly correlated with little lag, thus the price strongly determines secondary supply, which acts as a market-balancing mechanism. This demonstrates that ramping up secondary supply can happen quickly and reactively with the right incentives. Therefore, secondary supply can be an increasingly important source of copper supply particularly in times of supply shocks and price spikes, if the right policy incentives are in place. However, this also shows the difficulty in sustaining high scrap usage rates in a low-price environment.

Copper scrap use has decreased since 2015 from 18% to 17% of demand excluding direct use of scrap, and more significantly including direct scrap (from 37% to 33%). This is due to a combination of price, scrap trade restrictions from China, higher energy and shipping costs reducing recycling profitability, the impact of Covid-19, and that EU and US policies promoting domestic scrap collection have not yet taken effect. In climate-driven scenarios, however, copper scrap use increases significantly. In the NZE Scenario, the share of secondary supply in total demand rises to 20% by 2030 and 30% in 2040, excluding direct use of scrap. This growth is driven by strong policy efforts to increase collection rates, optimise sorting systems, raise policy mandates for recycling and encourage investment in new processing facilities and smelters. Growing end-of-life volumes from EV batteries also emerge as a major contributor from 2030. In the NZE Scenario, both sources of secondary supply experience strong growth, with direct use of scrap almost doubling from 2023 to 2040 while secondary production scrap increases by 2.5 times in the same period.

Supply: A major primary copper supply deficit develops after 2025

Expected mined copper supply from exisiting and announced projects and primary supply requirements by scenario



Notes: Based on mined output. Primary supply requirements are calculated as “total demand net of secondary supply”, also accounting for losses during refining operations. See Introduction for definitions of the base and high production cases.

Implications: A broad combination of supply and demand measures are needed to close the copper supply gap

Our analysis of project pipeline indicates that a copper primary supply shortfall may develop after 2025 in all three scenarios, despite the signficant growth in secondary supply. Even in the high production case where almost 2 Mt of extra mined supply is available shows a supply gap of 2.2 Mt (10%) to meet demand required by government climate pledges while there is a 4.5 Mt (20%) shortfall to match demand in the NZE Scenario in 2030. This demonstrates the urgency of financing and approving new supply projects given the long lead times to bring online new production. Beyond 2030 the supply gaps continue to expand as demand grows robustly for all scenarios. By 2040, base case supply would have to increase by 80% to meet APS demand while it would have to double to be on track to meet 1.5° C by 2050. Even in the high production case, supply would have to increase by 60% in the APS and 75% in the NZE Scenario by 2040 to meet demand. This anticipated primary supply deficit presents a growing concern for future clean energy technology deployment.

The most critical risk for copper is this major supply gap from 2030 onwards, being primarily driven by the strong increase in demand from clean energy technology deployment coupled with the declining ore quality in resources. For instance, the average grade of copper concentrate in Chile has decreased 30% since 2005. Although the implied supply gaps do not mean that achieving transition goals are unattainable, the substantial supply deficit requires a range of solutions to reduce pressure on primary copper supply requirements. This includes considerable supply and demand actions from governments and companies, including investment, substitution, material efficiency and recycling measures. The lack of diversification going forward, particularly in refining is also a key risk for the security of supply of copper.

Supply measures

First, on the supply side it is essential to stimulate significant investment in new primary supply, including in lower-grade plays. Governments can play a key role in supporting strategic projects financially and in streamlining permitting. However, the problem of declining ore quality poses a considerable challenge on the investment side, as there are few major new resources of high quality to exploit, also as a result of subdued exploration spending over the past decade. The tight supply market is likely to increase prices which could support investment in lower-grade plays, but pose economic pressures on end users. Many projects in the largest supply region, Latin America, which is also the region facing acute water stress challenges, are also facing critical social and environmental opposition, which has already resulted in the shutdown of the Cobre

Panama mine. This underlines the importance of governments and international mining companies working closely with the local community and ensuring benefits are felt to maintain social acceptability.

Recycling is one of the most crucial measures to reduce primary copper supply pressure going forward. Copper is one of few materials that can be recycled repeatedly without any loss of quality. Manufacturing scrap is already reasonably well recycled; however, end-of-life scrap and mining waste have significant potential for improvement. With global copper secondary supply currently 17% of demand (excluding direct use of scrap), but increasing to 30% in 2040 in the NZE Scenario, there is still substantial room for improvement. Given its multitude of applications, the global stock of copper is a critical resource, often referred to as the "urban mine", and further exploitation of this is crucial. One of the critical issues limiting copper recycling is the difficulty in economically sorting and separating copper and its alloy types from complex electronic post-consumer scrap, where the value of recovered copper is often not high enough to match the recycling cost. Second, collection infrastructure is often insufficient in many regions, with limited coordination between supply chain actors. This is compounded by insufficient incentives and information for consumers to recycle copper-containing products. Lastly, there is a lack of regulatory mandates on copper recycling and collection.

To address these challenges and enhance copper recycling, several actions are necessary. First, implementing comprehensive regulations is pivotal, including recycling rates and content mandates, bans on metals in landfills, and enforcement of design for recycling standards for new products to ensure a larger pool of products that are economically recyclable. Governments can support copper recycling supply chain coordination, which can reduce costs. Policy measures including China's "Green Fence" policy, restricting the import of low-quality copper scrap, has inadvertently resulted in scrap oversupplies in Europe and thus low-quality scrap not being accepted in recent years. Therefore, increasing the scrap pool without accompanying investment in processing facilities may be less effective. This reinforces the need for greater global coordination between copper recycling supply chain actors, coupled with improved tracking of global scrap flows. Second, governments can support and scale up collection and sorting infrastructure, including information campaigns and incentives for consumers. Third, support for novel emerging recycling technologies which can efficiently sort and separate copper and its alloys is crucial, for instance sensor-based scrap sorting such as X-ray fluorescence and laser-induced breakdown spectroscopy. Lastly, supportive trade policies and measures promoting the development of new processing capabilities, along with economic incentives aimed at sustaining higher scrap usage in times of lower prices, are essential.

Novel technologies offer promise for extracting greater amounts of copper from lower-grade plays and materials currently considered waste. For instance, primary sulphide leaching, bioleaching or hydrometallurgy can enable copper recovery from ores below mill head grade, typically considered waste. Advanced separation techniques can also concentrate and upgrade low quality ore. Machine learning has also been used not only to optimise processing operations but also in identifying new resources. Despite their promise, many of these technologies are still emergent and have to be proven at scale.

Demand measures

On the demand side, there are multiple measures which can be taken to relieve supply pressure. Increasing material efficiency is key to reducing copper demand. For instance setting mandates and standards for copper intensity in products such as construction pipes or wiring can be effective. Providing financial incentives for consumers to purchase high material efficiency products can also help, particularly in appliances. Copper intensity is being reduced in products such as electric motors and solar panels, where price is often a driver.

Substitution of copper where possible is an important measure going forward. Aluminium, though it has 60% of the electronic conductivity of copper, is the primary substitute option for many copper applications. It is also lower cost and lighter weight providing other potential advantages. There are applications where copper cannot be substituted including lithium-ion anode current collectors, due to lithium alloying with aluminium at low potentials. In networks aluminium's lower electrical conductivity requires thicker cables, while the inferior thermal and mechanical properties necessitates greater maintenance, therefore, aluminium is less suitable for high-voltage subsea and underground cables (although some OEMs are however starting to consider replacing copper in subsea applications).

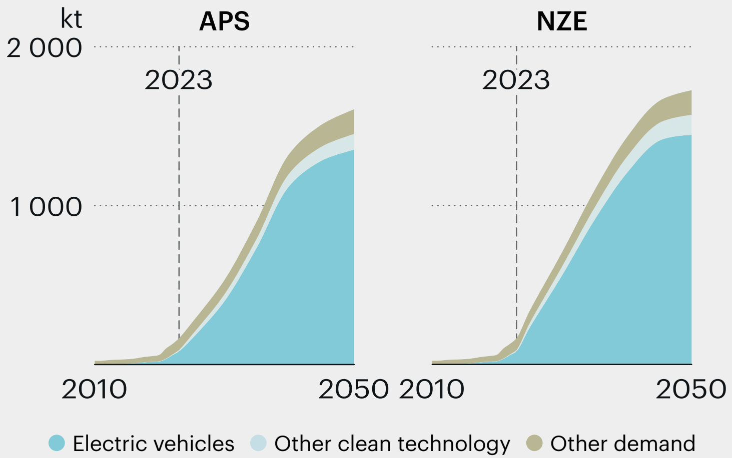
However, in many applications substituting copper is possible with commercial viability with minimal disadvantage. For instance, copper plumbing can often be replaced by plastic pipes such as cross-linked polyethylene (PEX) or high-density polyethylene (HDPE), though they can be difficult to recycle. Aluminium can replace overhead copper distribution cables, as well as copper windings in some motors, generators and transformers. However, it is also important to note aluminium processing is almost five times more carbon-intensive than copper processing; therefore, there are energy-related implications to substituting copper with aluminium.

Outlook for lithium

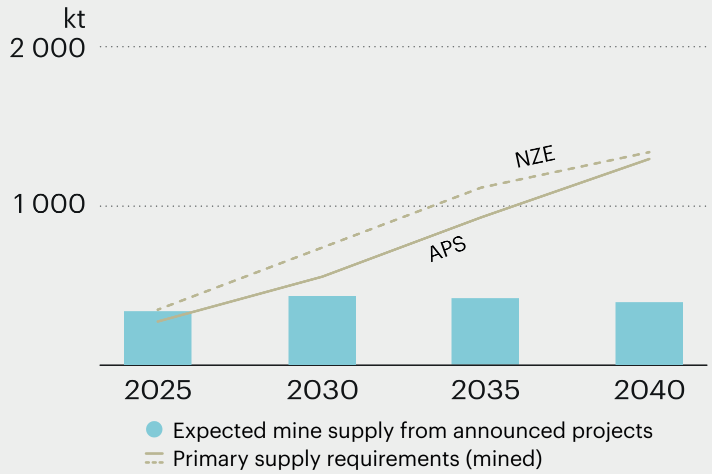
Lithium

Li

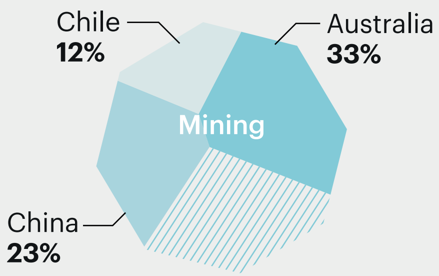
Demand outlook

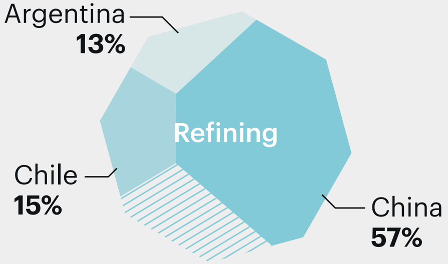


Mining requirements



Top three producers 2030





Milestones (APS)	2021	2023	2030	2040
Cleantech demand (kt)	**38**	**92**	**442**	**1 203**
Other uses (kt)	63	73	90	123
Total demand (kt)	**101**	**165**	**531**	**1 326**
Secondary supply and reuse (kt)	2	5	28	154
Primary supply requirements (kt)	**100**	**160**	**503**	**1 172**
Share of top three mining countries	89%	85%	68%	70%
Share of top three refining countries	100%	96%	85%	84%

Clean energy transition risk assessment

Supply risks

Highest

price volatility than other focus minerals

Geopolitical risks

85%

of refining by top three countries in 2030

Barriers to responding to supply disruption

Only

3%

of lithium sourced from secondary supply today

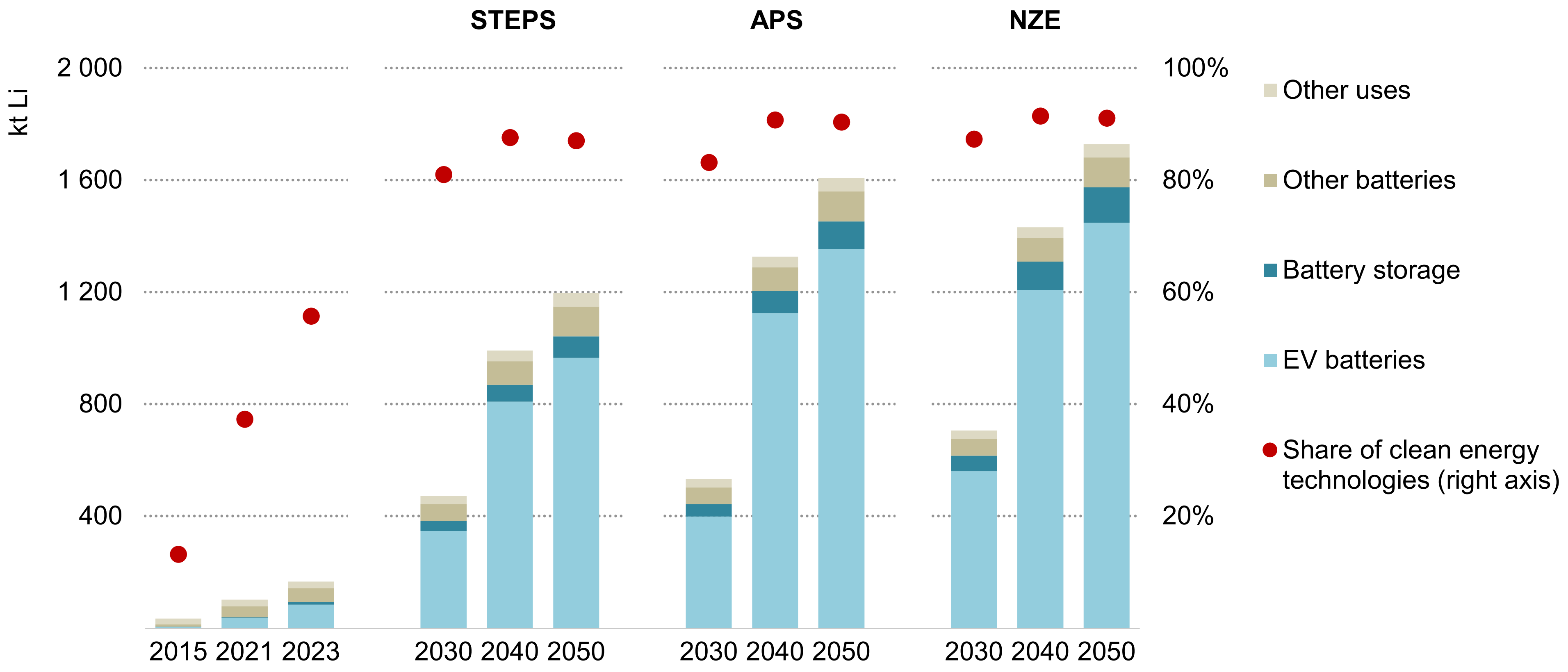
ESG and climate risk exposure

50%

of mines located in high, very high and arid areas

Demand: In clean energy transitions, lithium is the mineral facing the fastest demand growth

Global lithium demand outlook by sector and scenario



Demand: Lithium fuels the growth of the EV industry, and its demand grows tenfold to 2050 in the NZE Scenario, propelled by the rapid deployment of EVs

Lithium is used in a variety of applications such as ceramics or lubricants, as well as in small volumes in pharmaceuticals, but demand structure has deeply transformed over the last ten years, making batteries the dominant driver of global lithium demand growth. Lithium, one of the lightest metals in the periodic table, is the natural candidate for high energy density in batteries due to its superior electrochemical characteristics.

Lithium demand is set to rise almost threefold over this decade in the STEPS, expanding faster than all other focus minerals. By 2050, demand reaches 1 200 kt Li in the STEPS and 1 600 kt Li in the APS. In the NZE Scenario, demand increases to 1 700 kt Li by 2050, a tenfold growth from today's levels, driven by clean energy technologies.

Not only is lithium critical to clean energy transitions, but the lithium industry's ability to ramp up has allowed the EV industry to outpace industry expectations. The EV industry contributes to about 90% of future lithium demand growth between today and 2050 in the APS. Meeting the 1.5 °C climate objective requires particularly rapid growth this decade: in 2030, the EV sector's annual lithium demand is 40% higher in the NZE Scenario than in the APS.

Battery storage is currently a minor consumer of lithium, accounting for about 5% of demand, but its development accelerates by the end of the decade. In the NZE Scenario, lithium demand for battery storage rises to 130 kt Li in 2050, well over ten times the current demand.

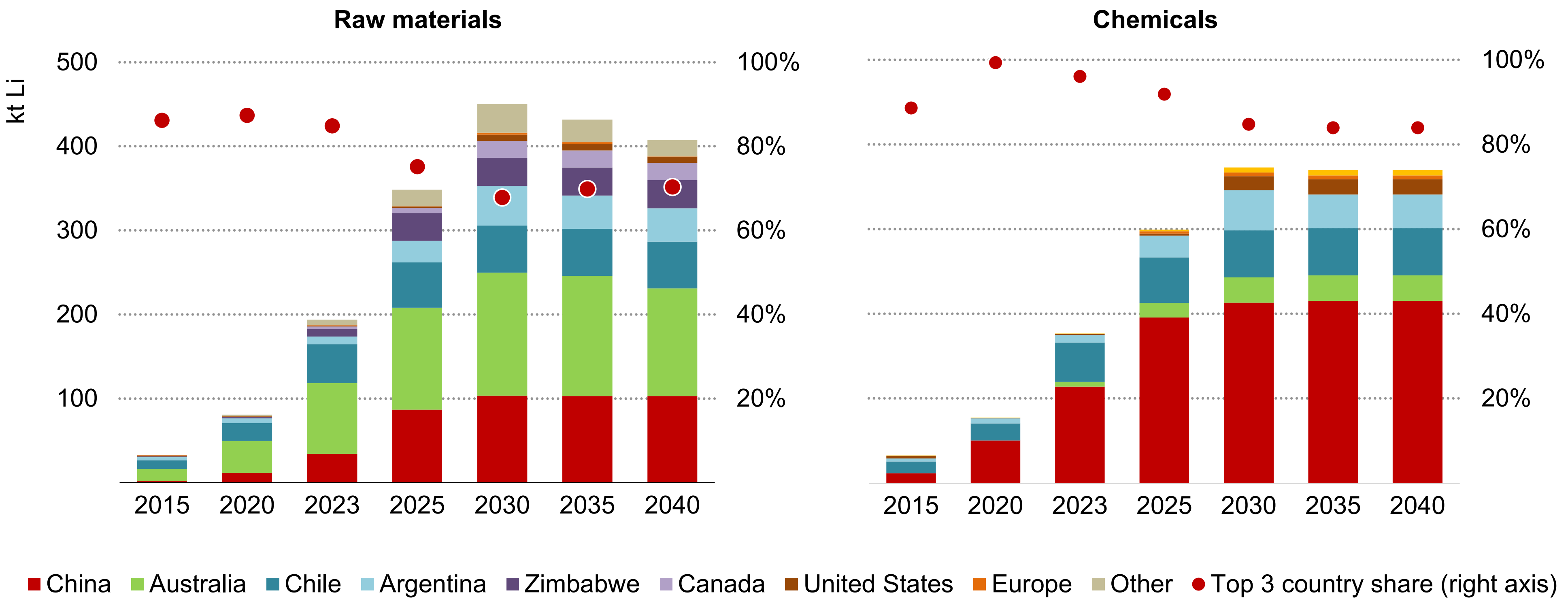
Lithium-ion batteries' role in fuelling the growth of the EV industry remains unchallenged in the near term. Alternative technologies such as sodium-ion batteries and vanadium flow batteries begin to take some shares from lithium-ion batteries in low-range vehicles and storage markets, but they do not materially alter the prospects for lithium demand in climate-driven scenarios.

In an alternative case of the NZE Scenario where sodium-ion experiences wider popularity within the EV market, total lithium demand could be reduced by 10% in 2030. Likewise, in the case of an early adoption of vanadium flow technologies, demand for lithium in storage applications could be reduced by 6%.

If technical challenges around their scale-up are overcome, solid-state batteries with lithium metal anodes could create a new market for lithium in metal form (as opposed to chemicals such as carbonates or hydroxides), of 200 kt Li in 2040 and 330 kt Li in 2050 in the NZE Scenario.

Supply: New lithium players emerge in Argentina and Zimbabwe; China continues to dominate refining of hard rock ore

Lithium raw materials and chemical production from operating and announced projects in the base case



Notes: Raw materials cover extraction of lithium from hard rock ore, as well as from clays and brines. Lithium chemicals cover the first production of lithium carbonate, hydroxide, sulphates and chlorides, and excludes reprocessing.

Supply: New players emerge on the mining side; refining takes different trajectories depending on chemical product

Mining

Today, annual production of lithium raw materials (from hard rock, brines and clays) amounted to around 190 kt Li in 2023, 70 kt Li from brines and 120 kt Li from hard rock. Lithium production has more than doubled in the past three years. The dominant producer of hard rock lithium is Australia, which produces 84 kt Li in the form of spodumene concentrate, mostly exported to China for refining. Another type of hard rock ore, lepidolite, is being developed, with a boom of production during the high price period of 2021-2023 in China's Jianxi province, providing 12 kt Li to the market in 2023. Brines are extracted in salt lakes of Latin America (46 kt Li for Chile and 9 kt Li for Argentina), but also from high plateaux in western China (14 kt Li).

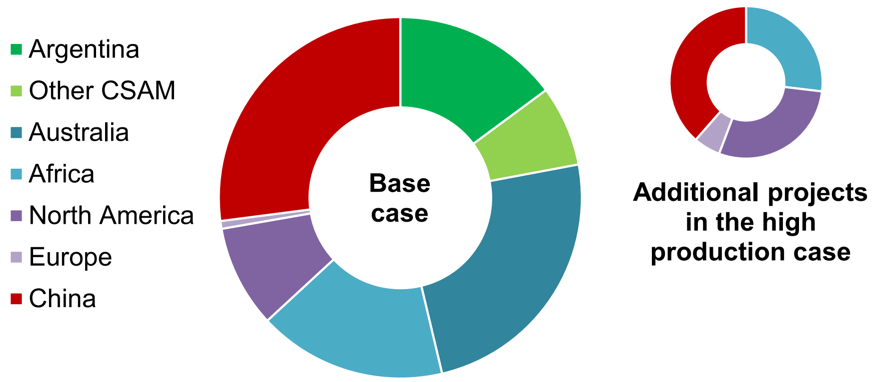
Analysis of announced projects indicates that lithium raw material supply grows to 450 kt Li around 2030 in the base case, again more than doubling the current production, and reaching five times the production of 2020. In the high production case, an additional 70 kt Li of raw material supply could be made available on the market. If announced projects come online as planned, this volume approaches the requirements in the STEPS as well as in the APS in 2030, but is insufficient to stay on the 1.5 °C pathway. Beyond 2030, all scenarios require a further investment in new supplies.to keep pace with the demand growth.

Australia remains a key producer of lithium with its spodumene deposits, through brownfield expansions of its major mines (Pilgangora, Greenbushes, Mount Marion and Wodgina) as well as several new projects, such as the Kathleen Valley and Mount Holland mines. Australia also hosts a first-of-its-kind tailings retreatment facility at Greenbushes, designed to extract further lithium from anterior mining waste. In the base case, Australia remains the largest producer in 2030, accounting for a third of world production.

China is the world's largest consumer of lithium as well as the world's largest refiner, but traditionally sourced lithium feedstock from mines overseas. Significant efforts have been made to develop domestic supplies, with notable investments in domestic mines from downstream manufacturers, such as CATL. The Chinese share of global lithium mining has steadily increased since 2016, from 6% to 17% in 2023. In the base case, it overtakes Chile and becomes the world's second-largest lithium producer in the mid-2020s.

Latin America has traditionally been a major lithium supplier with Chile's Salar de Atacama. Chile remains the continent's largest producer, but there are growing interests in Argentina, with a particularly strong pipeline of brine extraction projects. Based on announced projects, Argentina attracts over 80% of future capital investments for lithium in Latin America, with investors from all regions, from the United States and Australia, as well as Europe (Eramet), China (Ganfeng, Zijn, Tibet Summit Resources) and Korea (POSCO Chemicals). By 2030, Chile's base case annual supply grows to 56 kt Li, but Argentina emerges as a close contender, with 47 kt Li of production. Despite significant lithium resources in Bolivia (23 Mt, about a fourth of world known resources), projects have yet to emerge there. The country has signed an agreement with Russia's Rosatom and China's CITIC Guoan Group to develop its lithium resources and recently launched an international tender for lithium extraction, although significant challenges remain.

Geographical distribution of planned additional lithium mining projects, 2023-2030



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Note: CSAM = Central and South America.

Lithium mining is a recent phenomenon in Africa, where Zimbabwean production has recently ramped up, with 9 kt Li of lithium exported every year as concentrates of various hard rock ores (lepidolite, but also other minerals, such as petalite). Some informal artisanal and small-scale (ASM) mining activities have been reported in Nigeria, a phenomenon new to lithium, but frequent for other metals such as cobalt, gold, tin, tungsten and tantalum. Additional industrial capacities are planned in Zimbabwe, but other countries could follow suit, with projects in Ethiopia, Mali, Namibia, and possibly the Democratic Republic of the Congo and Ghana. In 2030, Africa's total lithium production in the base case rises to 53 kt Li, and further to 70 kt Li in the high production case.

There are many projects in the pipeline at their early stages of development, but price volatility may delay the projects coming up, particularly those outside of incumbent country producers, with implications for long-term supply and diversification.

Refining

Two regions have historically dominated the supply of lithium chemicals, with three distinct business models. Refining of lithium-rich brines of China and Latin America is done locally, and lithium is then exported as a refined chemical – whether carbonate or hydroxide. This process traditionally involved evaporation ponds, making this relatively water-intensive. To reduce water requirements, a diversity of new "direct lithium extraction" technologies are under development, but may involve higher operating costs, China currently dominates the refining of hard rock ore, from domestic resources, but also by refining the majority of lithium mined from hard rock overseas, notably from African countries and Australia. Lithium is generally mined and then locally processed into an exportable concentrate, but some African facilities, such as in Namibia, were built to directly ship ore to China.

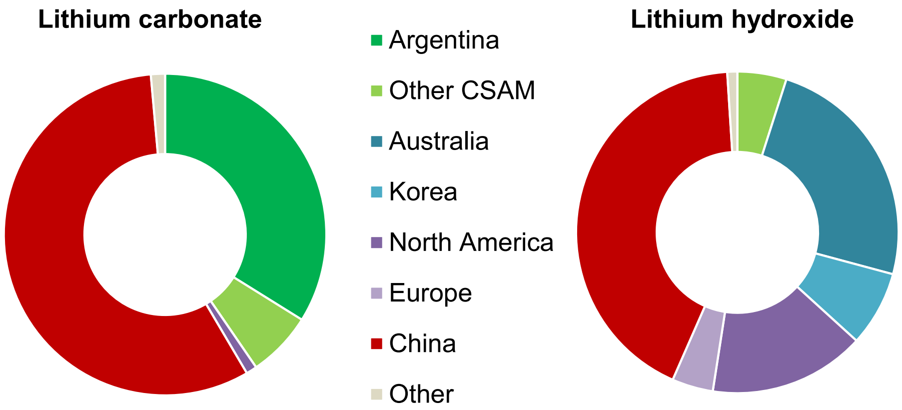
Some operations focus on conversion of one chemical into another, notably lithium carbonate to hydroxide, covering about 20% of current hydroxide supply, a technology dominated by China.

Lithium chemicals can be recycled from secondary resources, typically “black mass” either from end-of-life batteries or manufacturing scrap from gigafactories. Historically, battery recycling facilities focused on higher-value metals, such as nickel and cobalt, and lithium was often not recovered. Depending on prices, the uptake of lithium recycling may require policy incentives. A number of recycling companies are also achieving 90% recycling rates for lithium, and policy makers are strengthening recycling targets significantly, such as with the EU battery regulation, all of which could help scale up secondary supply of lithium. In the APS, the share of secondary lithium supply increases from a low level today to 10% by 2040.

By 2030, lithium carbonate production nearly doubles to 220 kt Li in the base case, and possibly 260 kt Li in the high production case, but the project pipeline leaves little space for diversification. The top three country share remains close to 98%, covered by Argentina and Chile (refining their domestic brines) as well as China, which remains the major hub both for its domestic extractive activities, but also for the refining of hard rock overseas into carbonates.

Projects being planned in other regions focus on lithium hydroxide, producing 170 kt Li in 2030 in the base case, and 185 kt Li in the high production case, more than twice the current production. The interest that investors take in hydroxide can be attributed to its dominance in North American and European demand, where the recent gigafactory projects almost exclusively focus on high-performance chemistries that require this chemical. The higher value of hydroxide is another aspect weighed by project developers, who anticipated a price premium relative to lithium carbonate.

Geographical distribution of planned additional lithium chemical projects, 2023-2030



IEA. CC BY 4.0.

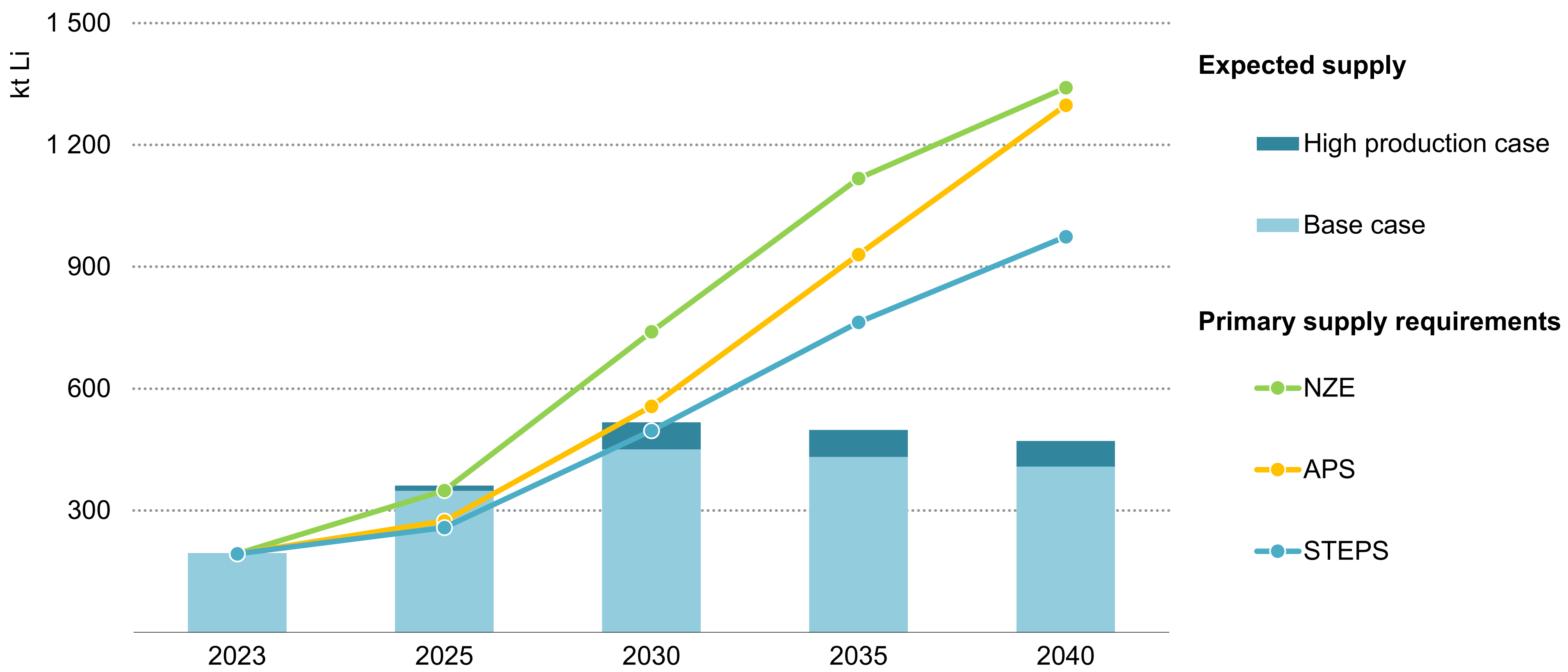
China traditionally dominated refining of lithium from hard rock ore into hydroxide and continues doing so in the base case. It remains the main player with 60% hydroxide market share in 2030. Until recently, Australia was entirely dependent on China for the refining of its lithium ores, but two refineries are currently ramping up to produce lithium hydroxide, producing 30 kt Li by 2030.

In other advanced economies, investors are also making bets on conversion facilities, importing carbonates and refining them into hydroxide closer to their consumers, with large plants including Albemarle's Megaflex projects, as well as AMG's Bitterfeld plant inaugurated in 2022 in Germany and POSCO's planned conversion plant in Korea, as well as recycling plants. In North America and Europe, mining projects tend to be integrated, associating a mine with a hydroxide refinery.

Projects are also being considered outside of lithium mining countries. Indonesia's growth in nickel-rich cathode supply chain makes conversion plants likely to emerge there. Three lithium refining projects are also being considered in Saudi Arabia and the United Arab Emirates. However, refining projects have yet to emerge in Africa.

Implications: Short-term supply is expected to keep up with demand, but further projects need to come through to serve demand growth in the medium to long term

Expected lithium primary supply from existing and announced projects and primary supply requirements by scenario



Notes: Based on raw material output covering extraction of lithium from hard rock ore, clays and brines. Primary supply requirements are calculated as “total demand net of secondary supply”, also accounting for losses during refining operations. See Introduction for definitions of the base and high production cases.

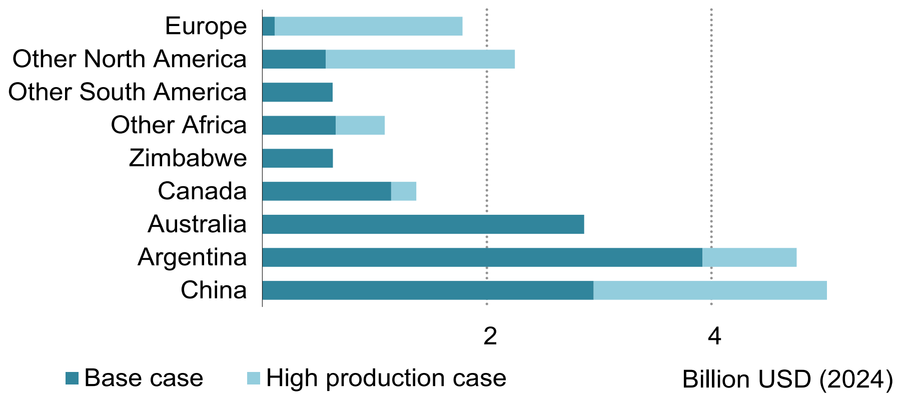
Implications: Investments are critical to keep pace with strong demand growth, but challenges remain in ensuring sufficient diversification and tailoring to future battery chemistry needs

Recent price volatility may lead to short-term supply responses, discouraging investment for new supplies. In February 2024, production in the world's largest mine, Australia's Greenbushes, was slowed, and other lithium producers announced plans to review their operations. Operating cost is one of the major considerations in production suspension decisions, but it is not the only factor. Those with long-term offtake agreements might continue even though their cost profiles are high, which could put additional pressure on prices beyond what supply-and-demand dynamics suggest. Symmetrically, integrated projects are reducing production, despite being on the lower end of the cost curve – such as Australian hard rock players.

There are risks that the current low-price environment may reduce investments in lithium projects, including those offering better ESG performance or outside of incumbent regions, which would affect medium- to long-term supplies. Many recent projects had been planned during periods of higher prices, and their viability may be reassessed if investors' long-term expectations are revised.

While the market is well supplied at the moment, continued investment flows are required to develop projects to serve long-term demand and diversification goals. At 2024 values, the current project pipeline in the base case requires USD 13 billion of investment for raw material production, with an additional USD 7 billion required for the high production case.

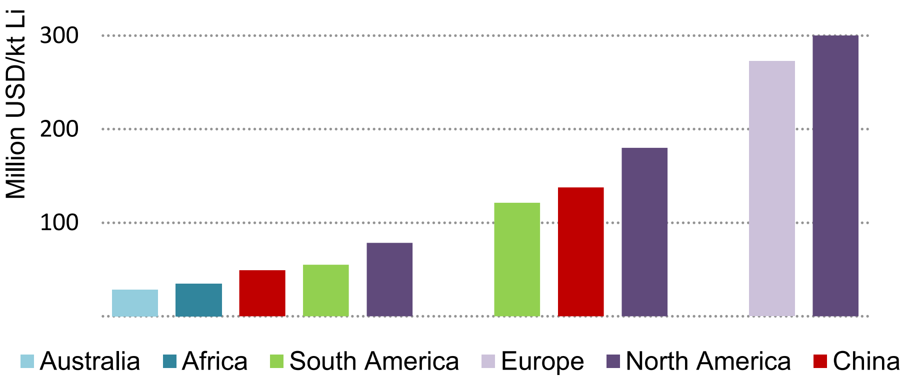
Cumulative capital investment requirements to support the current mining project pipeline in the base case, 2024-2040



Sources: IEA analysis based on company reports, Battery Materials Review.

Analysis of the project pipeline suggests that significant regional disparities exist in the capital costs for developing new projects. In particular, European and American lithium extractive projects generally require higher upfront costs. Business models often compensate for this disadvantage through integrated approaches offering highly refined products, but volatility in the refined chemical markets is putting price assumptions at risk.

Average capital intensity of lithium mining projects

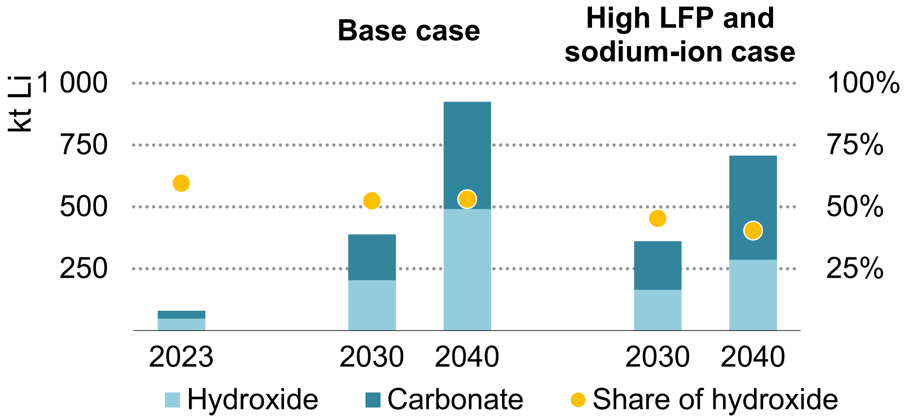


Sources: IEA analysis based on company reports, Battery Materials Review.

In the long term, concerns remain regarding geographical and ownership concentration. Two trends are emerging. First, efforts to increase domestic feedstock supplies from dominant chemical producers – notably progress achieved by China researching new deposits and promoting domestic mining activities, with the financial support of domestic downstream battery manufacturers. Geological considerations put Chinese plays at a competitive disadvantage historically, but new deposits under development may be changing this picture. Notably, miners are developing domestic spodumene projects, the same type of ore as Australia's lower-cost lithium mines.

The incumbent players' endeavours to procure resources abroad indicate that sustained supply concentration may exist through ownership – Chinese enterprises own most domestic ventures as well as major interests in Australian, Argentinian and African ventures.

Lithium chemical demand by type in the APS



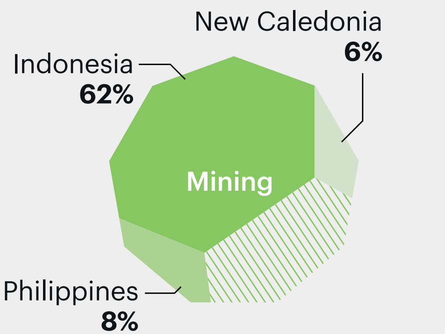
Finally, the lithium market structure is sensitive to the respective market shares of different battery chemistries, with growing supply chain segmentation between two chemicals: lithium hydroxide and lithium carbonate. Lithium hydroxide is required for nickel-rich chemistries, while carbonates are used both in the older generation of NMC chemistries and the LFP market. In the APS, EV requirements for carbonate and hydroxide are expected to rise in parallel, with hydroxide being required for 55% of total demand by 2030. In an alternative case where LFP takes a larger share, demand for hydroxide demand would be 25% less, calling for readjustments in regional sourcing strategies and project development planning.

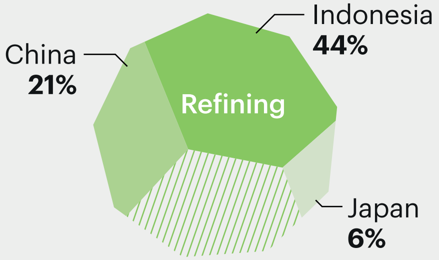
Outlook for nickel

Nickel

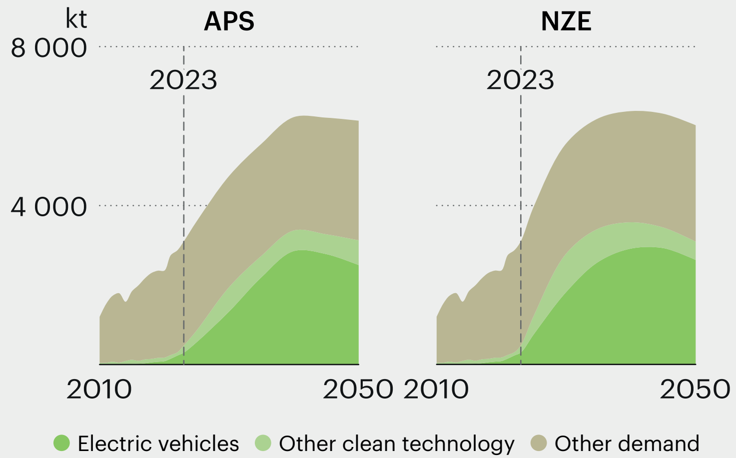
Ni

Top three producers 2030

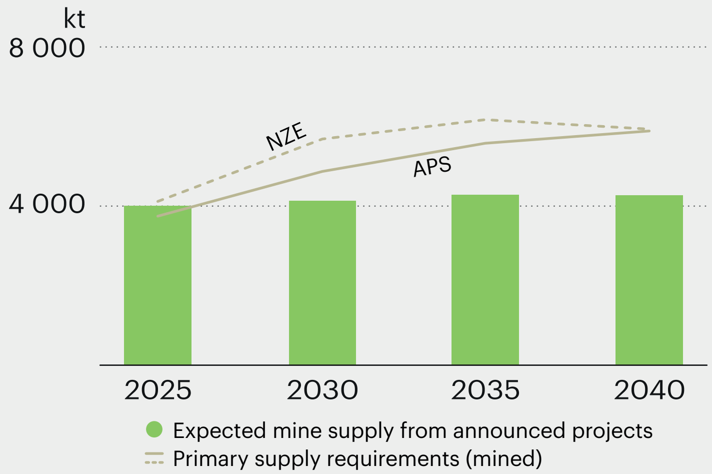




Demand outlook



Mining requirements



Milestones (APS)	2021	2023	2030	2040
Cleantech demand (kt)	**240**	**478**	**1 953**	**3 381**
Other uses (kt)	2 519	2 627	2 802	2 857
Total demand (kt)	**2 759**	**3 104**	**4 754**	**6 238**
Secondary supply and reuse (kt)	10	43	139	613
Primary supply requirements (kt)	**2 749**	**3 061**	**4 615**	**5 625**
Share of top three mining countries	60%	69%	76%	83%
Share of top three refining countries	66%	71%	71%	73%

Clean energy transition risk assessment

Low Med High

Supply risks

6%

of battery pack cost in 2023

Geopolitical risks

61%

of mining by one single country in 2030

Barriers to responding to supply disruption

1%

of nickel sourced from secondary supply today

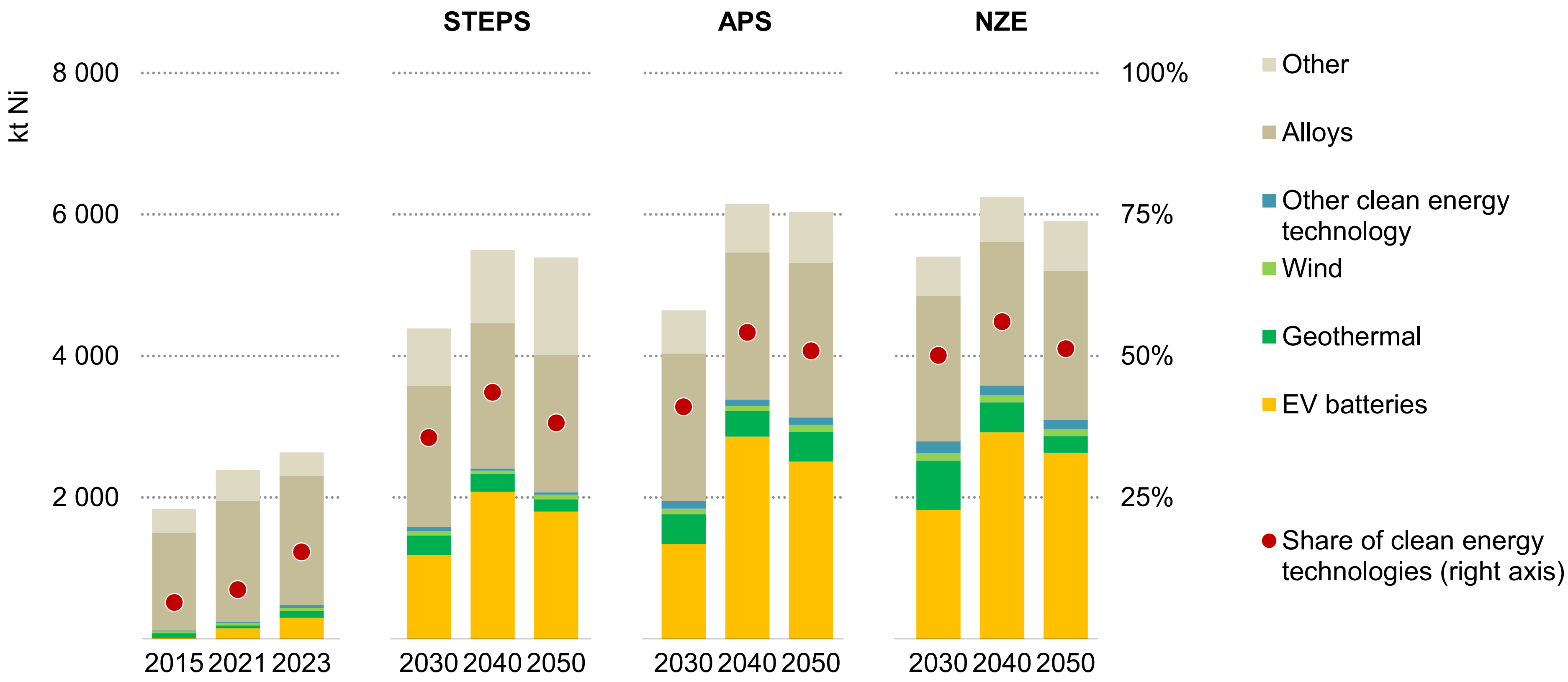
ESG and climate risk exposure

603 gCO_2/kWh

Among the highest average grid carbon intensity for refining

Demand: Growth in nickel demand is driven by clean energy applications; EVs become the largest-consuming segment in the coming decades in climate-driven scenarios

Global nickel demand outlook by sector and scenario



Note: Alloys includes both demand for stainless steel and for non-ferrous applications.

Demand: Nickel demand almost doubles over the period to 2050, driven by the rapid deployment of EV batteries

Nickel is used in a wide range of applications and is important for the broad economy with its use for alloys and stainless steel, as well as in the clean energy sector. The largest applications in the clean energy sector are within EV batteries, but nickel is also used in low-emissions power generation, such as in wind and geothermal energy.

Global nickel demand remained steady between 2018 and 2020 around 2.4 Mt, but then began to increase rapidly, reaching around 3.1 Mt in 2023. Demand is set to grow further in all scenarios, increasing to 4.5 Mt in 2030 in the STEPS. In the APS, demand growth is slightly higher, rising to 4.8 Mt in 2030. In the NZE Scenario, demand increases more rapidly to 5.6 Mt in 2030 as more EVs and low-emissions power generation are deployed. By 2040, demand under the NZE Scenario is slightly higher than the APS, but sees a larger fall to 2050 due to lower demand for uses in stainless steel as secondary supplies increase.

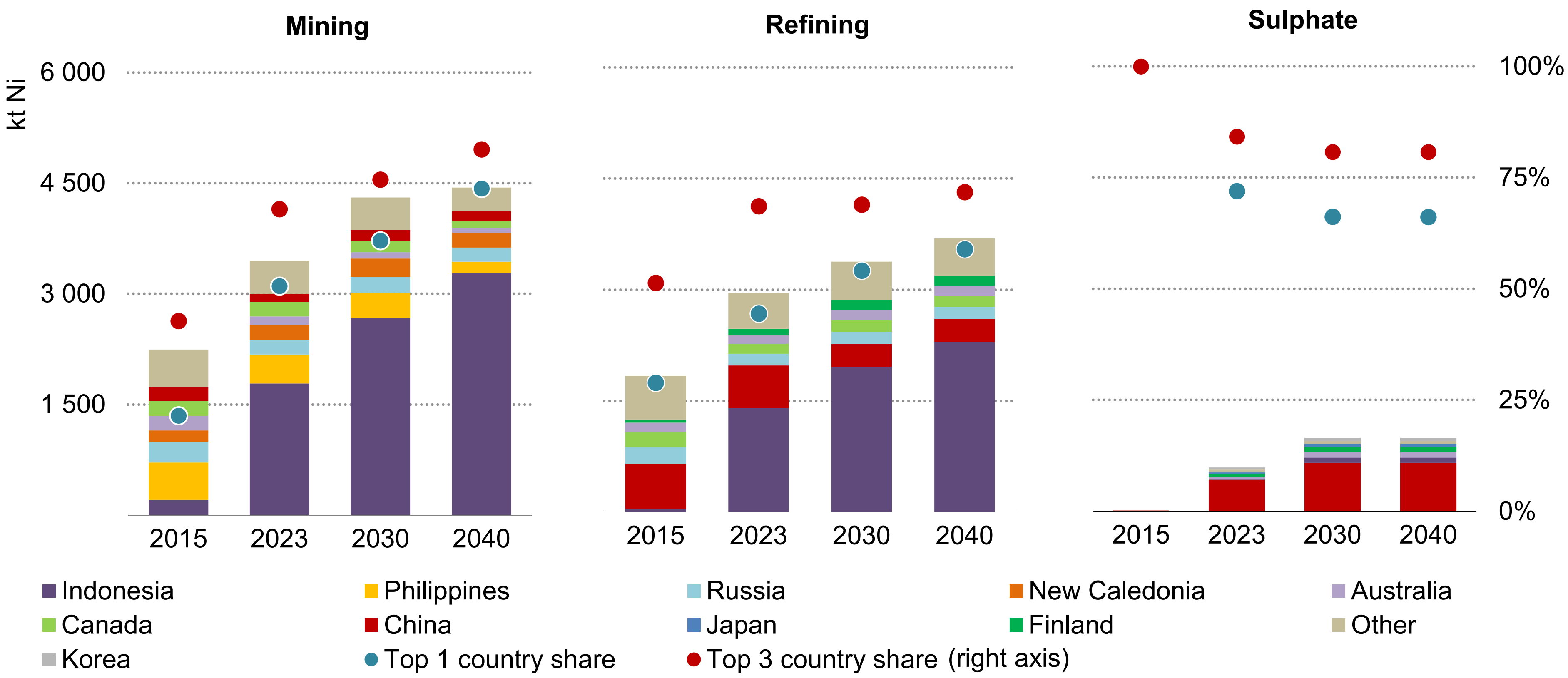
Historically, demand for nickel was primarily for its use in alloys (including stainless steel and non-ferrous applications): in 2015, 75% of nickel's total demand was for alloys. However, from 2020 to 2023 this shifted substantially and demand from the clean energy sector became the main factor behind a 30% increase in overall nickel demand over this period. This was primarily due to the increasing use of nickel-rich EV batteries, but was also driven by the use of nickel in low-emissions power. In 2023, the share of clean energy applications in total demand crossed 15%.

Looking to the future, nickel demand for alloys continues to play a large role in overall nickel demand with around 50% of market share in 2050 under the STEPS. In both the APS and NZE Scenario, the market share of nickel in alloys falls to around 35%, in part due to the higher clean energy demand but also due to lower material requirements for steel.

Nickel use in clean energy technologies continues to drive overall growth in nickel demand. In all scenarios, clean energy technology's share in total demand continues to rise, peaking at around 40% in the STEPS and around 55% in the APS and NZE Scenario by 2040 before falling slightly due to lower demand for nickel-rich chemistries. However, the primary driver in nickel's demand growth continues to be EV batteries in all scenarios, whose demand increases by approximately ninefold between today and 2050 in the APS and NZE Scenario.

Supply: Indonesia remains the largest producer of mined ore and refined primary nickel products to 2040; China dominates sulphate supply

Nickel production from existing and announced projects in the base case



Note: Nickel refining includes nickel that is processed into either a metal, oxide, nickel pig iron (NPI), or ferronickel and excludes outputs from intermediate production steps.

Supply: Intermediates sourced from laterite ores contribute to the largest growth in nickel supply, while conversion of laterite ores to battery-grade nickel continues to grow

Mining

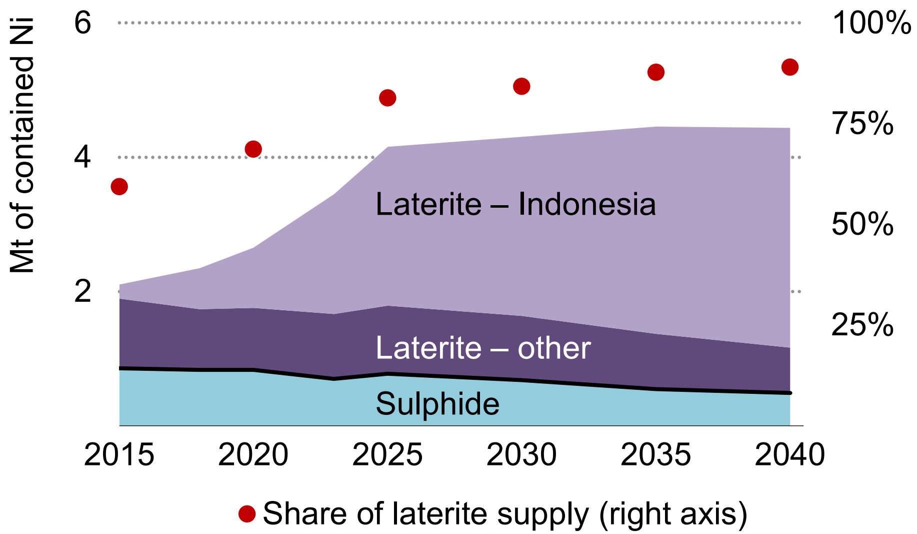
There are two types of nickel ore: laterite and sulphide. Laterite ores are primarily found in Indonesia, New Caledonia, the Philippines, and Australia, and sulphide ores are primarily found in Australia, Canada, Russia, and China.

Over the last five years, nickel mining has experienced significant absolute increases in the amount of material mined, as well as a shift in the type of ore mined. From 2018 to 2023, mined nickel supply increased by almost 1.5 times from 2.4 Mt to 3.5 Mt. This increase was primarily driven by the rapid expansion of mining in Indonesia, which saw a tripling in mined nickel output between 2018 and 2023, rising from just 0.6 Mt in 2018 to 1.8 Mt in 2023. Increases were also seen in Brazil, New Caledonia and Canada.

There has also been an increasing shift in the type of nickel ore, moving away from historically mined nickel sulphide to laterite. From 2018 to 2023, laterite mining nearly doubled from 1.5 Mt to 2.8 Mt, whereas sulphide mining fell slightly from 0.8 Mt to 0.7 Mt. This led to the share of laterites in total supply growing from 65% to 80%. In our base case, this trend is expected to continue until it reaches almost 90% in 2040, primarily driven by the growth in nickel mining in Indonesia, which almost doubles over the same period.

The mined nickel market has been increasingly geographically concentrated since 2018, with Indonesia's share of global production increasing from 25% in 2018 to 52% in 2023.

Mined nickel production by ore type in the base case



Looking ahead, in the base case, mined nickel supply is expected to continue growing to 4.4 Mt by 2040, marking a one-third increase from today. As our high production case assumes several early-stage projects come online, mined nickel supply grows to around 6 Mt by 2040, almost doubling. Geographical concentration is set to increase further in the base case, with the top three producing countries' share rising from 70% today to 83% by 2040. However, in the high production case, more projects come online from diversified regions, notably Australia and Brazil, bringing the top three countries' share slightly down to 81% by 2040.

In the near term, there could be some oversupply in the mined nickel market as a result of high investment into nickel developments in the last five years. In the longer term, expected supply from announced projects in the base case may fall short of meeting primary supply requirements in both the STEPS and APS by 2030. Additional projects that are assumed to come online in the high production case will need to materialise in this case. In the NZE Scenario, planned and high-potential projects fall short of primary supply requirements by 2030, requiring new projects to come through.

Refining

There are two types of primary nickel products: high-purity Class 1 products (containing 99.8% nickel or above) and lower-purity Class 2 products (containing less than 99.8% nickel). Battery cathodes need nickel sulphate, which has historically been produced from Class 1 products.

There are many stages of the supply chain to produce both Class 1 and Class 2 products. Intermediate products such as mixed-hydroxide precipitate (MHP) or mixed sulphide precipitate (MSP) are produced through hydrometallurgical processes such as bioleaching, and nickel matte is produced through smelting. Primary products such as nickel metals and nickel oxides, nickel pig iron (NPI) and ferronickel are produced through processes such as blast furnaces and electric arc furnaces, which can be used in end-use markets as final products. This section refers to the latter when discussing refined products.

Similar to nickel mining, refined nickel production has significantly increased over the last five years. From 2018 to 2023, refined nickel products grew 1.4fold to 3.1 Mt, primarily driven by growth in Indonesia, which saw an almost fivefold increase in production. Geographical concentration of the top producing country, Indonesia, grew from 30% to 45%, whereas geographical concentration of the top three producers grew from 50% to 70%.

Looking ahead, analysis of the project pipeline indicates that refined nickel production continues to grow in the base case, to 3.9 Mt in 2040. The largest driver of this growth is in NPI and nickel metals, each growing by around a quarter to 2040. This production is primarily driven by Indonesia, which sees an over 1.5-fold increase in refined nickel product production to 2040, primarily in the form of NPI, ferronickel and nickel metals. The top producing country – Indonesia –

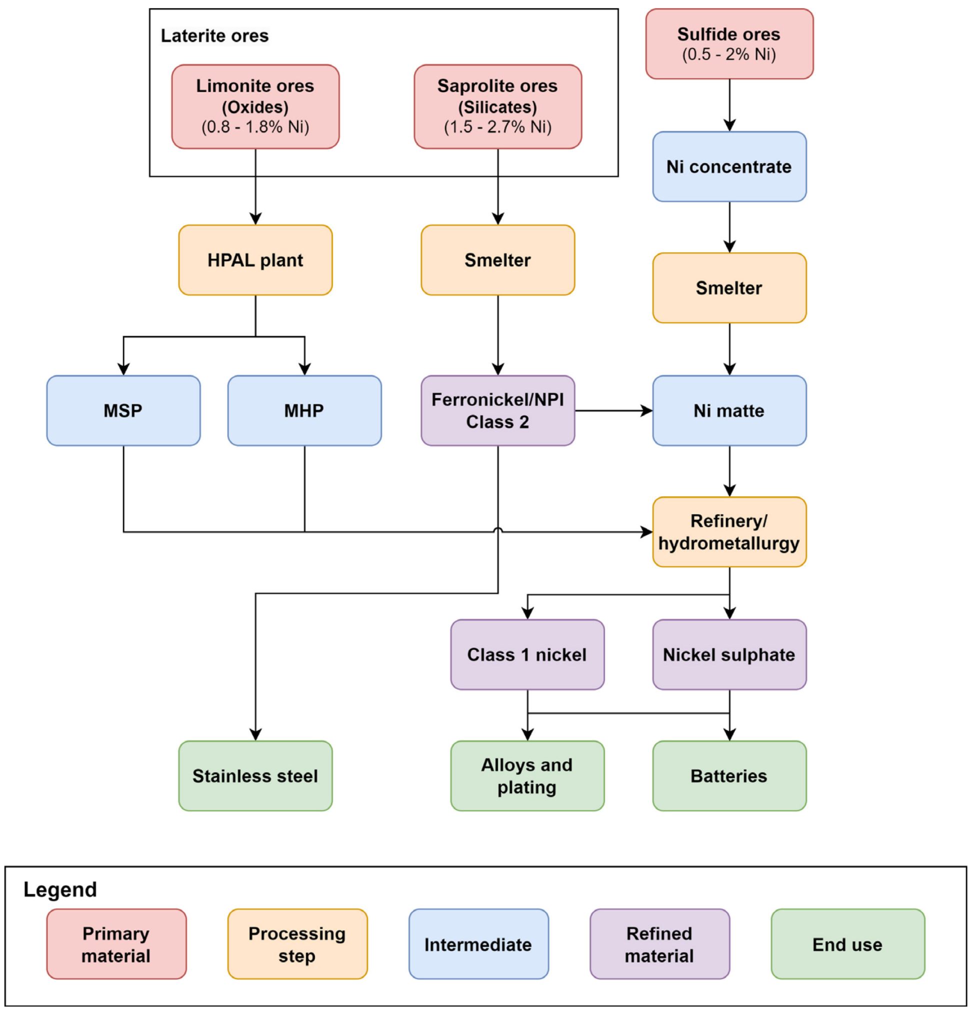
continues to maintain a dominating market share, growing from 45% in 2023 to 59% in 2040. The high production case does not see a much higher refined nickel supply. While there is slightly more production in countries outside of the dominant producer, such as Australia, the level of concentration barely changes compared with the base case.

Sulphate

For use in EV batteries, nickel needs to be further processed into nickel sulphate, which is then used as input into battery cathodes. Historically, nickel sulphate has been obtained through refining sulphide ores into nickel matte or nickel metals and oxides pellets and then into battery-grade nickel as it requires high-content nickel. Recent nickel market developments, including high prices and Indonesia's rise in prominence within the supply chain, have led to using MHP and MSP, sourced from laterite ores, as inputs for nickel sulphates. There has also been a rise in converting NPI and ferronickel – typically used in stainless steel applications – into nickel matte, which is then processed into nickel sulphate.

From 2018 to 2023, the most significant increase in inputs for nickel sulphate production was from matte via sulphide ores. Over the same period, there was also a rise in the production of nickel sulphate from matte via laterite ore and the intermediate MHP derived from laterite ore. In the base case, we anticipate this shift towards utilising matte via laterite and intermediates from laterite ores to continue through 2030.

Nickel supply chain



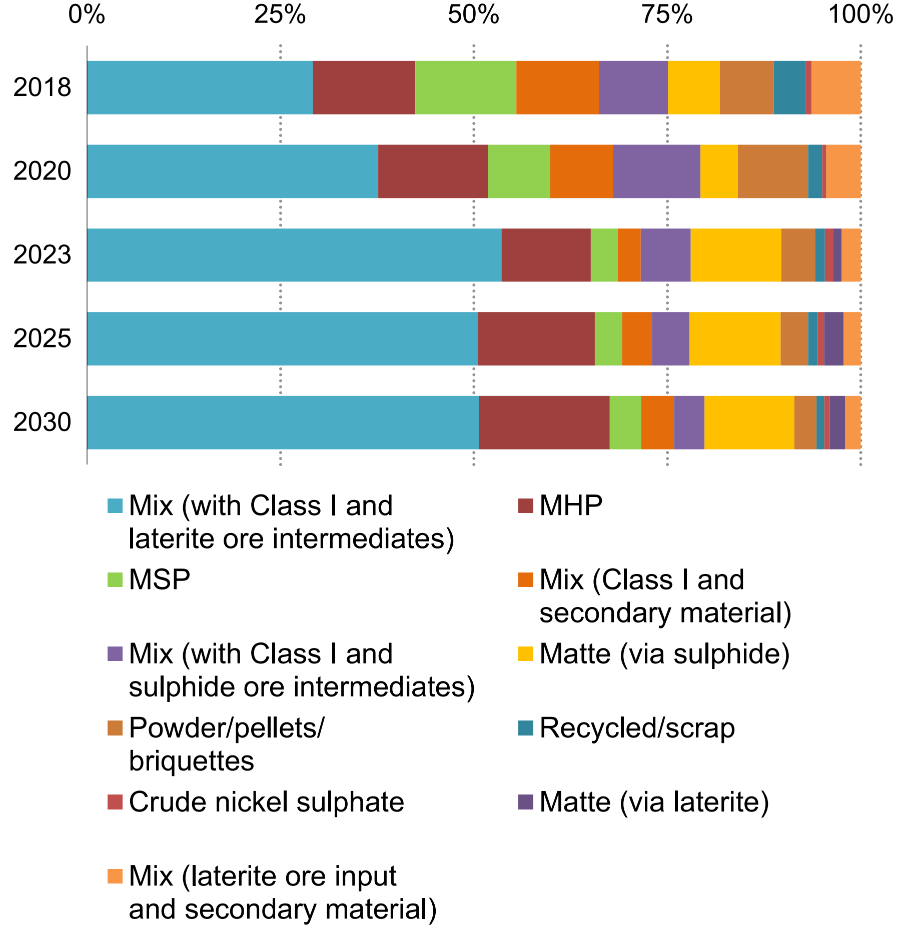
Note: HPAL = high-pressure acid leaching.

There is also large growth in the utilisation of a mix of inputs into nickel sulphate production, with the largest absolute increase seen in a combination of Class 1 and laterite ore inputs, through either MHP or matte. Mixes combining Class 1 and recycled material or scrap also increase to 2030. In our high production case, while slightly more sulphate projects that utilise matte via sulphide may come online, the primary input drivers are expected to remain as laterite ore inputs.

The surge in processing laterite ore for nickel sulphate production has been chiefly propelled by Indonesia, and the country is poised to maintain its leading role in driving growth in this sector. In the base case, Indonesia sees an over twofold increase in MHP production and an increase of 1.4 times in matte production by 2030.

In the near term, nickel sulphate may be adequately supplied to 2025. However, in both the APS and NZE Scenario, nickel sulphate requirements exceed expected sulphate supply from announced projects by 2030 and beyond, even with increases in sulphate supply from secondary production as more EV batteries are deployed and recycled. However, new sulphate capacity can be introduced relatively quickly – within 18-24 months – and we expect that supply can be relatively responsive to developments within the EV battery industry.

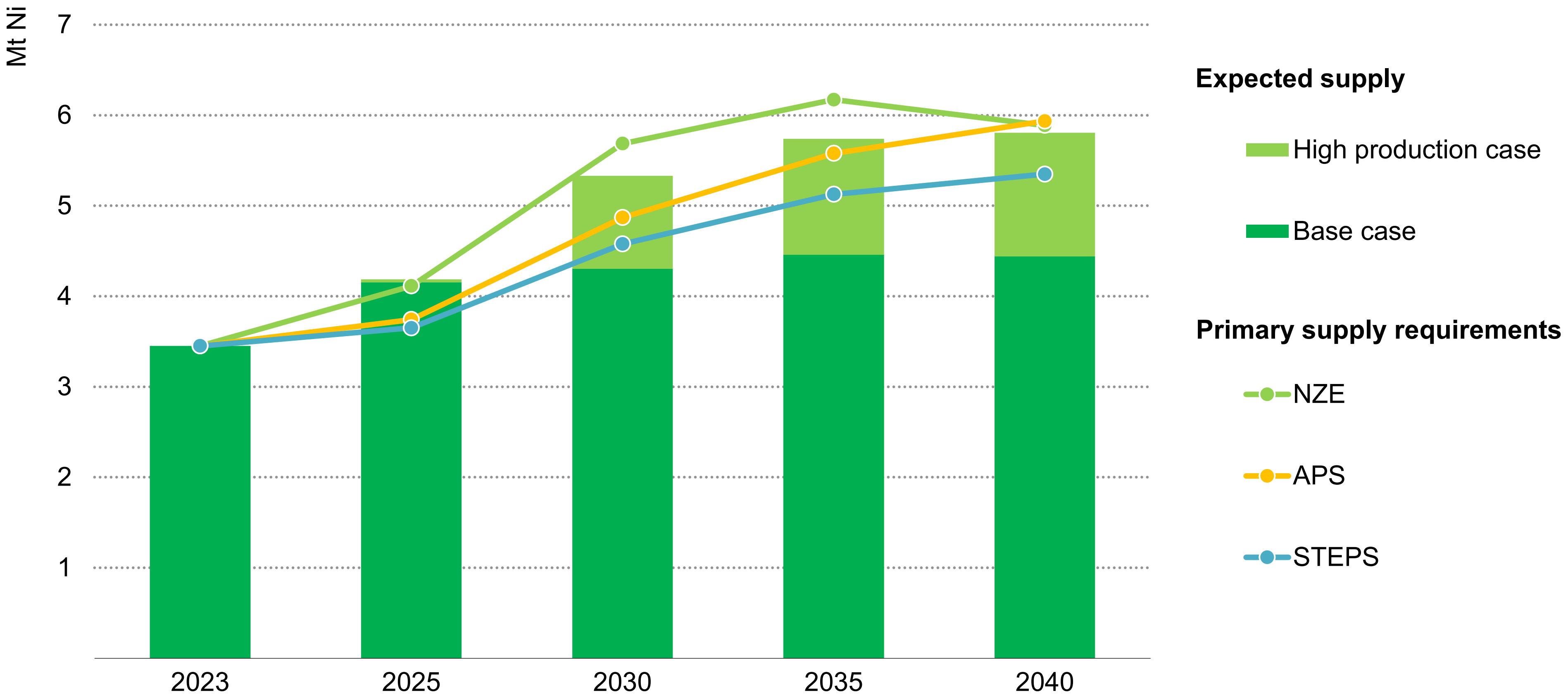
Inputs into nickel sulphate production



Note: Included in Class 1 is power/pellets/briquettes.

Supply: The market could be well supplied in the near term, but additional projects need to come through to meet demand in climate-driven scenarios in the medium and long term

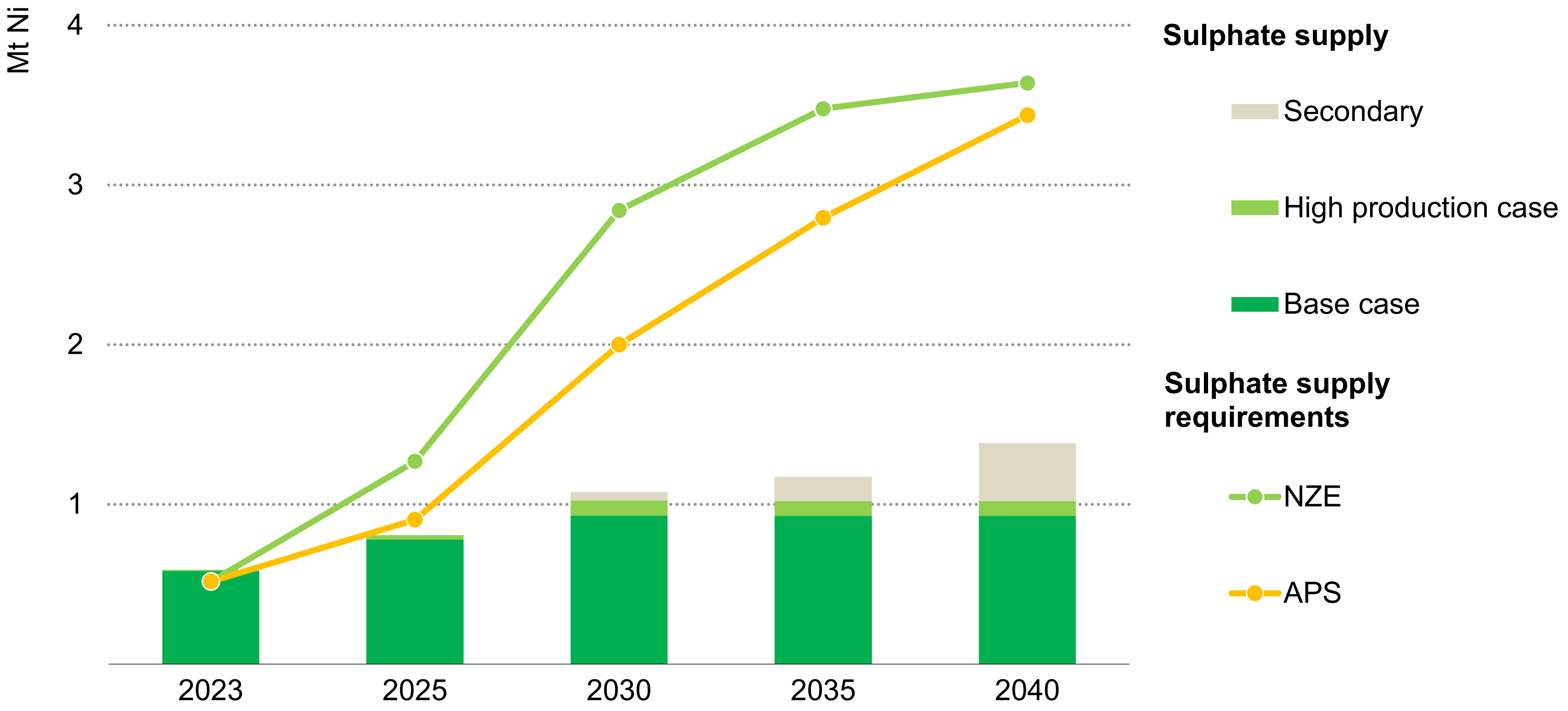
Expected mined nickel supply from existing and announced projects and primary supply requirements by scenario



Notes: Based on mined output. Primary supply requirements are calculated as “total demand net of secondary supply”, also accounting for losses during refining operations. See Introduction for definitions of the base and high production cases.

Supply: Analysis of the current project pipeline indicates that battery-grade nickel may see potential supply gaps in climate-driven scenarios by 2030, even with secondary supply

Nickel sulphate supply and demand balances based on existing and announced projects



Notes: Sulphate supply requirements includes nickel demand from EV batteries and demand from non-batteries. Does not include a route where precursor cathode material is directly produced from refining operations.

Implications: Today's low-price environment creates risks for future nickel supply and for the prospects for greater diversification

The recent low-price environment for nickel prompted several nickel producers to implement cost-cutting measures at existing operations. For instance, First Quantum's nickel mine announced production cuts, while BHP's Nickel West operations reduced its workforce. Additionally, other producers, such as Glencore's Koniambo nickel mine, placed their operations into care and maintenance. Consequently, nickel production in 2023 was lower than anticipated, with announced nickel mining production cuts and closures totalling around 80 kt.

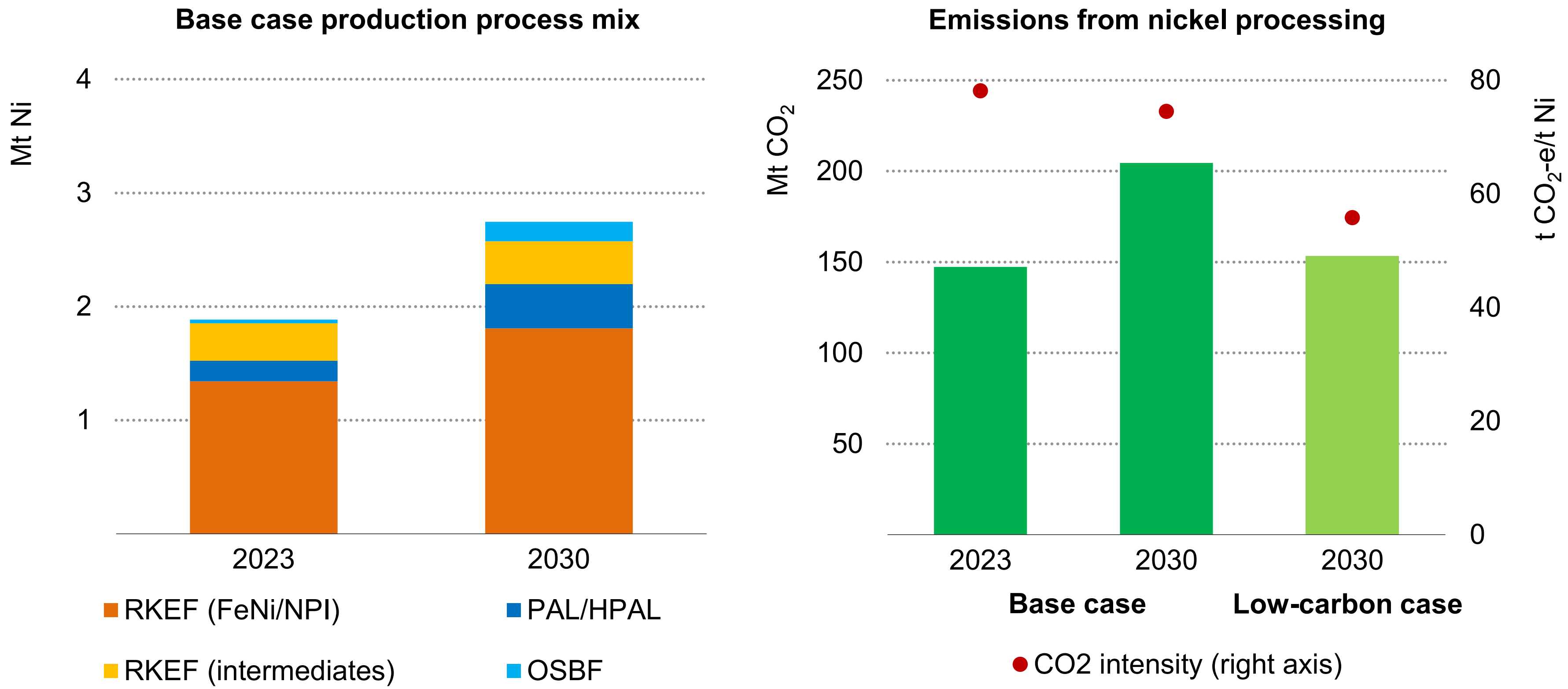
While the continuation of low nickel prices supports the growth of the EV market by keeping battery prices low, there is a potential downside: it may lead to further closures of nickel mines or halt ongoing developments. Operations such as BHP's Nickel West are contemplating putting their mines under care and maintenance, while New Caledonia's production faces the risk of investor loss. Reports have surfaced of producers halting project development due to nickel's low price, which threatens the long-term profitability of projects such as IGO's Cosmos nickel project. This risk of closure and development halts is especially pronounced for projects with higher costs and lower margins, often located in regions beyond the current dominant producers.

We have identified approximately 25 operating or potential mines that could be at risk if the current low nickel price persists, primarily located in Canada and New Caledonia. While closures of these nickel mines and production cuts may not immediately result in a significant undersupply of mined nickel, given that the market is currently well-supplied, they could lead to a shortfall in supply compared with medium-to-long-term demand in the APS and NZE Scenario. The total supply loss would be around 360 kt of supply in 2030 and 280 kt in 2040, respectively, almost 10% of supply in each year.

The larger concern stemming from the continuation of the current low-price environment is the potential closure of high-cost nickel mines, which would further reduce the diversity of supply in an already geographically concentrated market. If all at-risk nickel mines were to close, this would increase Indonesia's market share — the top nickel mining country — and the top three countries' share by around 6 percentage points in both 2030 and 2040.

Implications: Without greater efforts to shift to less energy- and emissions-intensive processes, emissions from Indonesian nickel production are set to increase

Indonesia nickel processing volumes and associated emissions



Notes: CO_2-e = carbon dioxide equivalent; RKEF = rotary kiln electric furnace; OSBF = oxygen-rich side blowing furnace; PAL = pressure acid leaching. The low-carbon case adopts "best case" intensities from the Minviro paper, which assume that processing operations are utilising renewable electricity and, where possible, non-coal thermal energy and reductants.

Implications: Indonesia has a major role in shaping the global nickel market

In both the base case and high production case, Indonesia's role in the global nickel market continues to expand as the country boosts its mining, refining and nickel sulphate production capacities. Indonesia's laterites ores are converted into nickel ready for conversion to battery-grade nickel by two methods: through processing to MHP or MSP through hydrometallurgical processes such as HPAL or the production of ferronickel or NPI through electric furnaces such as RKEFs, which is then converted into nickel matte.

Emissions per tonne of nickel vary by processing method. Currently, the emissions intensity of nickel production is estimated to be about 65 t CO_2-e to 105 t CO_2-e for RKEF and 10 t CO_2-e to 60 t CO_2-e for HPAL depending on the source of electricity and thermal energy or reductant utilised. These variations between processes primarily stem from the higher energy intensity of the laterite-to-NPI via RKEF process, which requires more electricity – around 500 kWh more per tonne of feed – as well as a greater direct use of carbon-intensive chemical reductants and heat energy sources.

In 2023, the primary production route of nickel in Indonesia was RKEF (to produce ferronickel or NPI), which accounts for almost 90% of production, resulting in an estimated 150 Mt CO_2 emissions from nickel production in the country. In both supply cases, operational ramp-ups and new projects in Indonesia lead to a shift in the production mix towards less energy-intensive processes. By 2030, the share of RKEF production is projected to decrease to around 80%, remaining stable through 2040. Meanwhile, HPAL is expected to increase its share of the production mix to approximately 15% by 2030. Additionally, OSBF processes also see a growing role, rising from 2% of the production mix in 2023 to 6% by 2030 in the base case.

This transition away from RKEF towards less energy-intensive processes could, on its own, lead to a reduction in the overall CO_2 intensity per tonne of refined nickel in Indonesia, from around 80 t CO_2 per tonne to around 75 t CO_2 per tonne by 2030. Despite this decrease in average intensity, if Indonesia's power and thermal energy sources for nickel processing remain dependent on coal, as they do today, absolute CO_2 emissions from nickel refining could be 1.4 higher in 2030 and 1.6 times higher in 2040, compared with 2023.

Indonesia is working to shift its energy mix to cleaner sources, which, in line with a long-term goal of reaching net zero emissions by 2060, could help to reduce the carbon impact of the country's nickel production. There are indications of some near-term progress by industry players. For example, one company is developing several HPAL projects while exploring replacement of coal with lower-emissions alternatives such as gas and bioenergy.

However, significant work remains to lower the carbon footprint of nickel operations, with measures that address energy demand requirements and emissions from power, chemical and thermal energy processes. As an illustration, if the Indonesian production processes projected in this report's base case were to reduce their CO_2 intensity to the "best case" levels identified in the Minviro paper, which assumes that processing operations utilise renewable electricity and, where possible, non-coal thermal energy and reductants, their average CO_2 intensity would decline by 25% ("low-carbon case"). Absolute CO_2 emissions would be similar to today's levels in 2030 and 20% higher in 2040 than today, despite the almost 65% increase in production.

Moreover, refining and processing operations often cause air, land and water pollution, in addition to significant carbon emissions, and there are trade-offs between the two commonly used processes for converting laterite ores to intermediates for battery-grade nickel. The process of using HPAL results in high waste production but has lower emissions intensity, whereas RKEF results in less waste but extremely high carbon emissions.

There are other environmental issues that could arise from Indonesia's growing role in the nickel market. The shallow, open-pit mining methods used in Indonesian nickel production have led to significant deforestation and the clearing of farmland. Research estimates that the direct land footprint of nickel mining in Indonesia amounts to 42 m^2 per tonne of nickel contained in ore. Under the base case production, this would equate to around 800 km^2 of additional land use impact between today and 2030.

In addition, tailings management associated with HPAL production is a persistent issue. While initial proposals for deep-sea tailings placement were dropped over environmental concerns, the alternative, land-based dry tailings stacking, still faces technical challenges driven in part by Indonesia's warm and humid climate. Hydrometallurgical waste from HPAL plants can be neutralised, dried and compacted by lining with geotextiles or thick clay layers to prevent waste stream leakage. However, significant investments in drainage and filtration systems are required to mitigate the impacts of high rainfall.

The use of captive power for nickel in Indonesia

One of the main drivers behind high emissions intensity of Indonesia's nickel is the reliance of the country's power on fossil fuels, especially coal, which make up 81% of the on-grid electricity mix. Approximately a quarter of current coal-generated power in the country is not grid-connected, known as "captive power", and serves energy-intensive industries, especially minerals processing, which are viewed as important to realising Indonesia's industrial strategy. Coal plants integrated with industries that support value addition in the natural resources sector or have a major contribution to job creation and/or national economic growth are exempted from the moratorium on development in Perpres No. 112/2022.

Over the last ten years, Indonesia has seen an increase in captive coal power capacity, which rose nearly eightfold from 1.4 GW to 10.8 GW. Without a shift in the business plans, technology choices and regulation of such plants, growth is likely to continue, with estimates of the pipeline for new captive coal power ranging from 14.4 GW to over 20 GW by 2030.

Around two-thirds of existing captive coal plants service the operating nickel smelters in the country, which are located in places that are not well integrated with the grid-connected power system.

Growth in smelter capacity and captive power to support it was driven in part by the country's export ban of nickel ores in 2020. In Central Sulawesi, the location of the Morowali Industrial Park, there is almost 1 Mt of production capacity and about 2.7 GW of captive coal power in operation, with a further 2.8 GW under construction. The locations of many of the other nickel refining operations in the country – Obi Island and Weda Bay – also have many operating and planned captive power operations.

To prevent a substantial rise in CO_2 emissions as nickel production expands, Indonesia will need to accelerate the uptake of low-emissions alternatives to captive coal power and find ways to phase out existing captive coal plants, as part of an overall strategy to shift Indonesia's nickel sector to a low-emissions pathway. The Just Energy Transition Partnership plans to develop a study on transitioning the captive power sector, building on Perpres No. 11/2022. Indonesia also released an Indonesian Taxonomy for Sustainable Finance which incorporates provisions for financing coal plants, aiming to expedite their closure. However, according to the taxonomy, new captive coal plants may be classified as a transition asset, and thus still eligible for finance, if involved in the processing and mining of critical minerals for the energy transition, such as nickel.

Implications: A price premium for low-emissions nickel?

As low-cost, high-emissions Indonesian nickel has come at scale to the global nickel market, market stakeholders have called on policy makers to support pricing mechanisms that can support the market for more sustainably produced nickel. However, the London Metal Exchange (LME) rejected calls to create traded contract specifications that would support a price premium for low-emissions or responsible nickel, citing concerns about market liquidity and interest as well as a lack of an agreed definition of "green."

Instead, the LME has highlighted its partnership with Metalshub, a digital platform for metals procurement and trading, as a way to help market participants assess potential premiums for "cleaner" nickel. Metalshub, in collaboration with a consultancy Minviro, plans to integrate nickel's carbon footprint data into the Metalshub procurement platform. While Metalshub does not play an active role in facilitating price determination in the way that an exchange like LME does, its recent announcement to begin reporting volumes of low carbon Class 1 nickel could contribute to market-based price discovery for a "green premium." LME and Metalshub have defined "low-carbon" nickel as having a carbon footprint lower than 20 t CO_2-e.

Similarly, Fastmarkets and Benchmark Mineral Intelligence, price reporting agencies, have proposed launching price assessments to distinguish cleaner nickel. The Fastmarkets specification would use self-reported transaction data to identify whether, and at what levels, the market is paying a premium for nickel briquettes with a carbon footprint of less than 18 t CO_2-e, whereas Benchmark's assessment considers transaction data for nickel sulphate sourced from companies assessed to be "industry leading" within their proprietary ESG scoring system.

The Fastmarkets and Metalshub emissions thresholds would exclude ferronickel and NPI production due to their relatively high carbon footprints but may still allow some production from HPAL pathways. However, it should be noted that the non-emissions environmental impacts associated with HPAL routes may require a more holistic view of sustainability that goes beyond the carbon footprint alone.

Despite efforts by market participants, it is difficult to imagine a significant premium emerging voluntarily, at least at a level that would support higher-cost producers to restart or maintain production. Processing and manufacturing industries are sensitive to raw material input prices, and voluntarily paying above market price for feedstock is likely to significantly impact their competitiveness. Regulatory intervention may need to play a key role in incentivising the production and consumption of responsibly sourced materials.

Subsidies or tax credits could be used to support the production of responsibly sourced nickel, with those provided under existing provisions such as the Inflation Reduction Act given only to producers that source a certain percentage of their nickel supply from "responsibly sourced" supplies or whose upstream greenhouse gas emissions are below a certain threshold. In addition to its nickel finance assistance programme, Australia is considering introducing nickel production tax credits similar to those in the IRA, which considers giving a production tax credit of 10% to critical minerals producers. Such tax credits might be tied to emissions, giving preferential rates to low-emissions producers.

Pricing differentiation between different sources of nickel could also be established through carbon pricing and trading schemes. The European Union's Carbon Border Adjustment Mechanism (CBAM), which imposes a carbon tax on imported energy-intensive goods, could be expanded to include other raw materials such as nickel or the embedded emissions in downstream products, such as stainless steel. Disclosure policies, such as the EU Battery Regulation which by 2025 will mandate battery producers to disclose the complete carbon footprint of EV batteries over their life cycle, could also make it easier for purchasers and consumers to determine the emissions of different nickel sources, which could support voluntary adoption.

At a minimum, all these actions would require policy makers to develop criteria to distinguish between supplies based on ESG performance. Establishing a common understanding of what supplies should be prioritised would require collaboration among industry stakeholders, policy makers and environmental experts to develop a robust and widely accepted framework that takes into account not only greenhouse gas emissions but also other environmental and social impacts across the supply chain.

All of these policies and industry actions should ensure that producers follow the principle of additionality, ensuring that product emissions are meaningfully reduced over the longer term. Calculations of emissions also need to be meaningful and across the supply chain, avoiding "greenwashing". Policy makers can support this by creating regulations that mandate reporting and disclosure requirements for emissions. Examples include the US Environmental Protection Agency's Greenhouse Gas Reporting Program (GHGRP) which requires large metal manufacturing facilities to report their emissions annually under specific methodologies that incorporate those of the Intergovernmental Panel on Climate Change (IPCC).

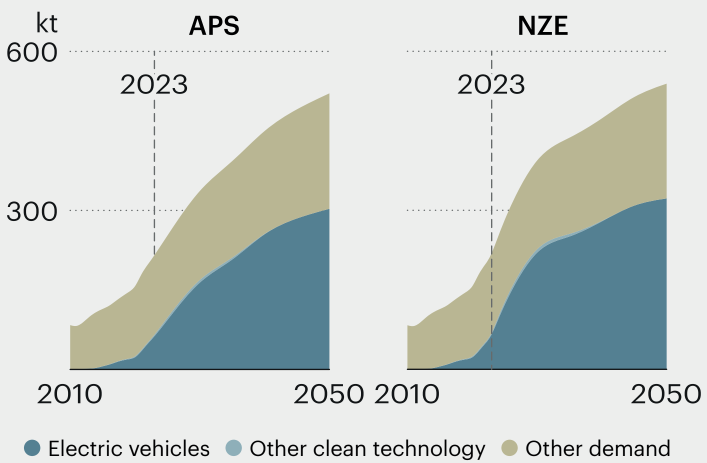
On the demand side, industry can also take actions to start incentivising responsible sourcing. For example, the First Movers Coalition aims to leverage the collective purchasing power of major market participants to create early markets for low-emissions steel, aluminium, cement, etc. By committing to purchase a proportion of their future supply from low-emissions sources, coalition members aim to send a demand signal to incentivise clean material production at scale. This type of approach could also be taken on a bilateral basis by industry players in the downstream EV market. Some of these players have already showed a preference for low-emissions nickel, such as Vale's long-term offtake agreement with Tesla, which emphasised secure access to low-emissions nickel.

Outlook for cobalt

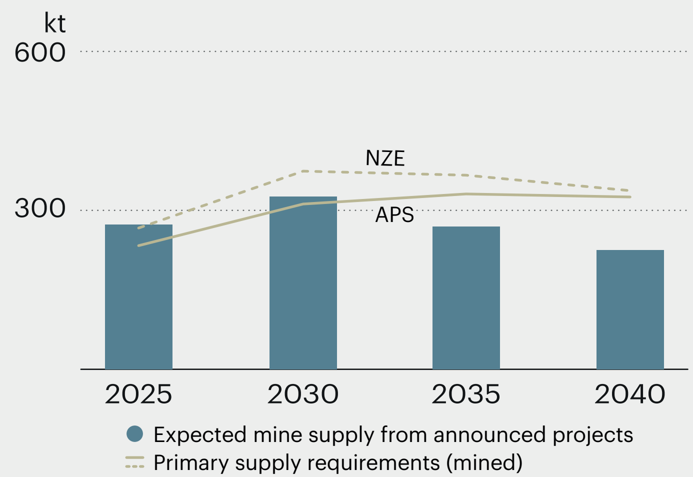
Cobalt

Co

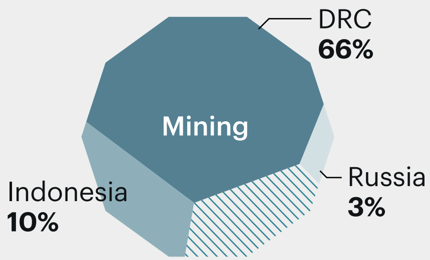
Demand outlook

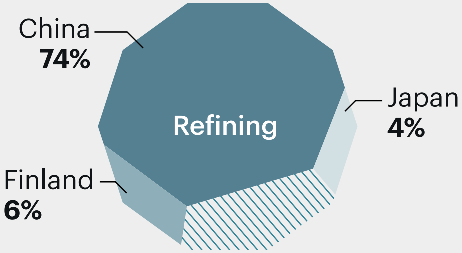


Mining requirements



Top three producers 2030





Milestones (APS)	2021	2023	2030	2040
Cleantech demand (kt)	**36**	**64**	**177**	**260**
Other uses (kt)	145	150	167	194
Total demand (kt)	**181**	**215**	**344**	**454**
Secondary supply and reuse (kt)	15	24	45	131
Primary supply requirements (kt)	**100**	**166**	**299**	**323**
Share of top three mining countries	75%	77%	84%	84%
Share of top three refining countries	86%	88%	84%	85%

Clean energy transition risk assessment

Low Med High

Supply risks

16%

shortfall in project pipeline vs. 2035 APS mining requirements

Geopolitical risks

84%

of mining by one single country in 2030

Barriers to responding to supply disruption

Growing adoption of

low-cobalt

chemistries

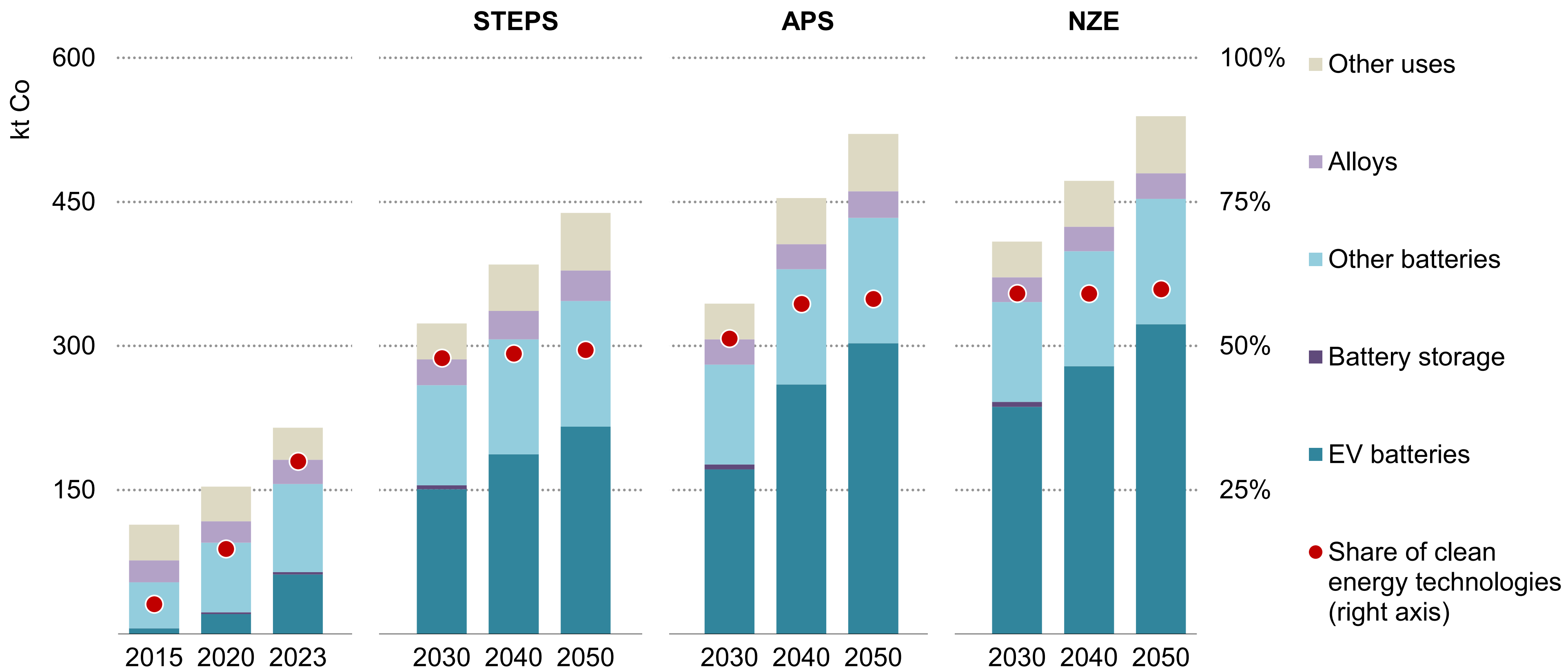
ESG and climate risk exposure

Low

environmental and social performance for mining

Demand: Cobalt demand increases robustly with growing EV deployment, but to a lesser extent than other battery metals due to the market preference for low-cobalt or cobalt-free cathodes

Global cobalt demand outlook by sector and scenario



Demand: EV batteries emerge as the largest segment of cobalt demand, despite the growing trend towards low-cobalt or cobalt-free EV batteries

Cobalt demand has grown strongly in recent years, with traditional usage supplemented by uses in EV batteries. In 2023, the non-clean energy technology sector accounted for around 70% of total consumption, while EV batteries accounted for the remainder. Within the non-clean energy sector, portable batteries used in electronics represented the largest share. Although absolute demand sees a slight uptick, its proportion of total cobalt demand diminishes to 25% by 2040 in both the APS and NZE Scenario.

Cobalt demand for EVs triples in the STEPS by 2040, grows by more than fourfold by 2040 in the APS and 4.5 times in the NZE Scenario from today. EV batteries take up the largest share of total cobalt consumption by the end of this decade, and their share rises to 60% by 2040 in the NZE Scenario.

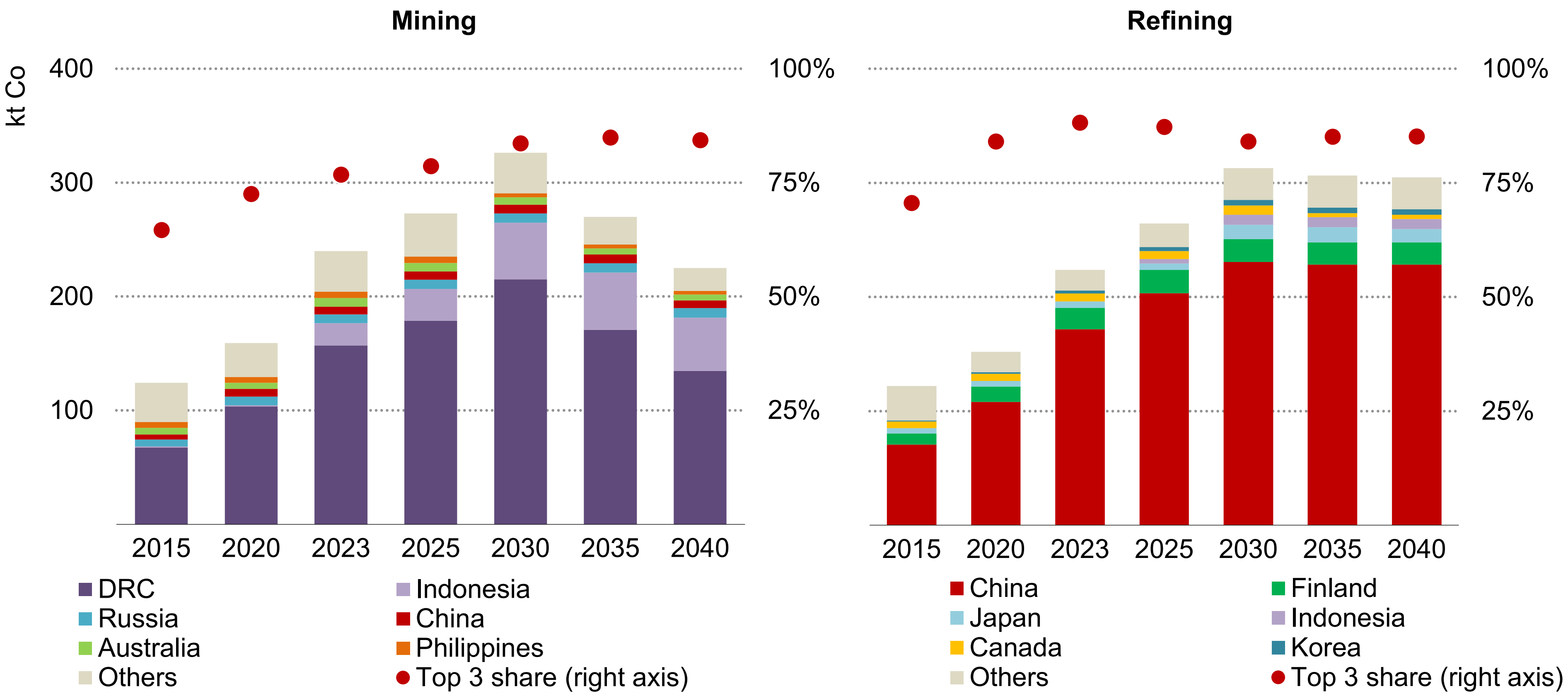
While demand for EV batteries continues to rise, the recent trend towards low-cobalt or cobalt-free batteries is slowing the pace of long-term growth compared with other battery metals such as lithium and nickel. In recent years, LFP cathode chemistries have rapidly expanded their market share in the EV industry, reaching a 40% share in 2023. Alternatives to lithium-ion batteries, particularly sodium-ion batteries, are also gaining traction in the EV market. It will take time for this relatively new technology to reach a full commercialisation, but the rise of alternatives implies a smaller piece of the EV-battery pie left for cobalt. Even among the traditionally popular NMC chemistries, the market is increasingly favouring chemistries with lower cobalt intensity. However, while alternative batteries with low or no cobalt are gaining traction, the overall size of the EV market continues to expand, supporting continued demand growth in the medium to long term.

Cobalt's role decreases steadily for battery storage, reaching negligible levels by 2050 in both the APS and NZE Scenario. Compared with EVs, storage batteries are not limited by space constraints, so the market is heading towards cheaper alternatives with lower energy density such as LFP cathode chemistries or sodium-ion batteries, neither of which contains cobalt.

Outside of batteries, cobalt was used the most in superalloys integral to the military and aerospace industries due to its pivotal role in providing strong resistance to corrosion, extreme temperature and high pressure. Demand for cobalt in superalloys continues to remain robust. The industries consuming these superalloys are typically less price-sensitive, thus ensuring relatively stable demand, as evidenced by recent price trends where cobalt metal alloys consistently maintained higher prices than cobalt sulphate during periods of price downturns.

Supply: The already high geographical concentration of both mining and refining processes further intensifies as current dominant players continue to expand their operations

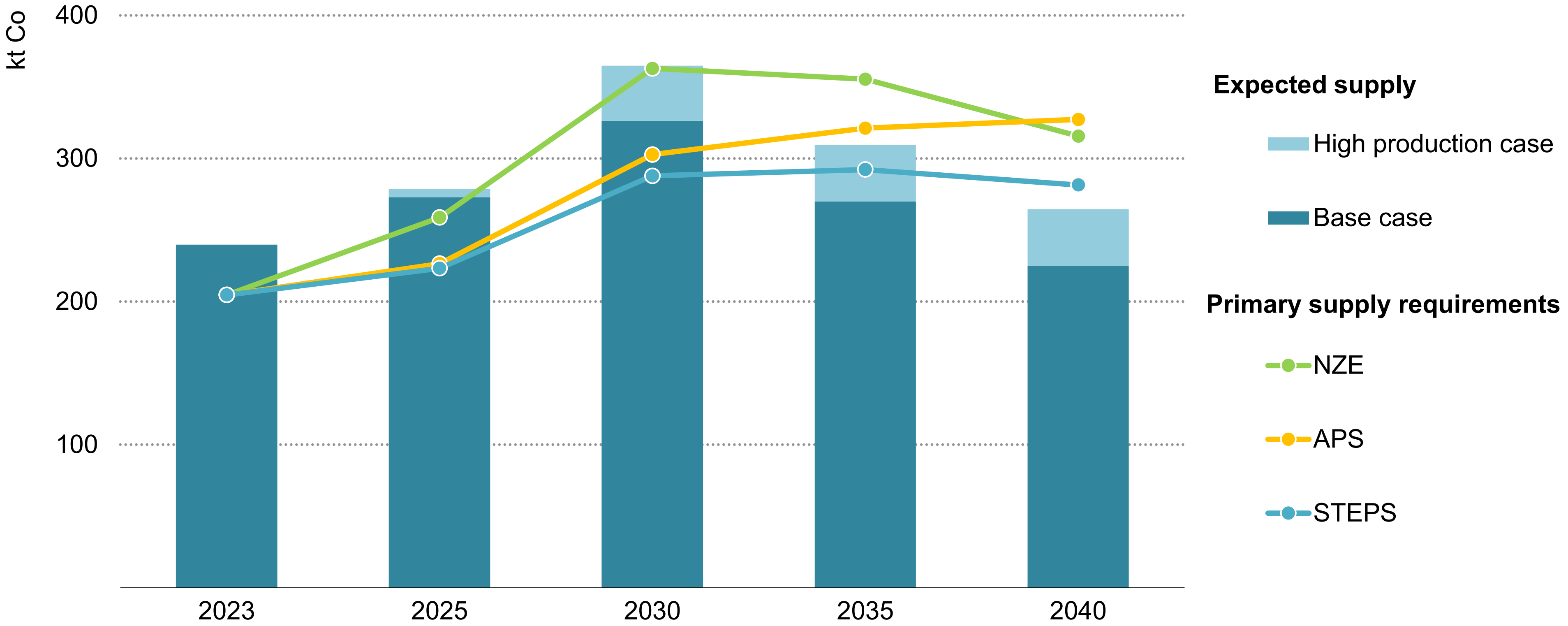
Cobalt production from operating and announced projects in the base case



Note: DRC = Democratic Republic of the Congo.

Supply: Analysis of announced projects suggests an increase in cobalt supply to 2030 before falling steadily with declining ore grades

Expected mined cobalt supply from existing and announced projects and primary supply requirements by scenario



Notes: Based on mined output. Primary supply requirements are calculated as "total demand net of secondary supply", also accounting for losses during refining operations. See Introduction for definitions of the base and high production cases.

Supply: A tale of two suppliers: the DRC and Indonesia

The cobalt market is well supplied today. In the near term, the current oversupply may continue with supplies from new mines and previously stockpiled volumes coming online in the Democratic Republic of the Congo (DRC). In the long-term, global mined supply begins to subside from 2030 as reserves in the DRC deplete although strong growth from Indonesia partly offsets this decline. Future cobalt supply could face major challenges as the current low-price environment makes financing new projects more challenging.

The DRC, the traditional No. 1 supplier

Mined cobalt production in the DRC is poised for significant growth in the near future as several new mines ramp up their output. China-based CMOC's Tenke Fungurume mine (TFM) resumed exports in April 2023 after resolving a royalty dispute with Gécamines, the DRC state-owned mining company. TFM's second-phase expansion began operations in the second half of 2023, with output estimated to reach 30 kt by 2027. Another major project by CMOC, the Kisanfu copper-cobalt mine started production in the first half of 2023 and is expected to contribute an average of 30 kt of cobalt per year by 2026 once it reaches full capacity. The Kinsevere copper mine's expansion under the China-based MMG Group, commenced operations in 2023 and is anticipated to produce 5 kt of cobalt annually in the near term. The cobalt output from China-based Jinchuan Group International Resources, which operates an open-pit Ruashi mine and is currently advancing the underground Musonoi mine in the DRC, is expected to surge by 75% to 10 kt in 2024. These sizeable new cobalt mines are anticipated to contribute significant volumes to the near-term supply pool, countering the slower production from non-Chinese major cobalt miners.

In the long term, existing mines in the DRC are likely to reduce their supply or close down due to diminishing ore grade and increasing production cost, resulting in a 15% drop in production from today's level by 2040 in the base case. Glencore's Mutanda mine may experience a reduction of up to 15% in annual production due to the depletion of oxide ore deposits on the surface. To sustain production levels, the cobalt-rich DRC would need to explore new deposits, re-evaluate old tailings, or transition its open-pit mines to underground operations. It is important to highlight that the DRC still possesses substantial high-grade resources. However, unlocking this potential necessitates new investments, a task that may pose challenges during periods of weak cobalt prices and ample market supply although robust copper prices could help.

Indonesia, the fast-rising second place

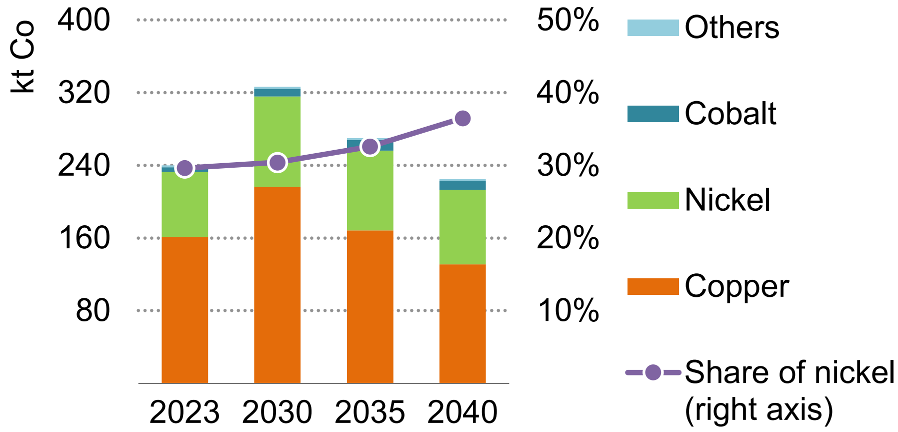
As of 2023, Indonesia had ascended to become the world's second-largest cobalt supplier. Indonesia's cobalt production rose by almost 20 times in the last four years since the Indonesian government nickel ore export ban drove an influx of investments in domestic nickel-cobalt processing operations including HPAL facilities. In the base case, Indonesia's cobalt production more than doubles to 2030, reaching 50 kt. In the high production case, its supply is estimated to reach 80 kt by 2030, constituting 23% of global cobalt supply, nudging the DRC's production share down from 65% in 2023 to 50% by 2040.

Cobalt as a by-product

Cobalt is mostly extracted as a by-product of copper ore or nickel ore. Traditionally, the primary mineral from which cobalt is refined as a by-product has been copper due to the abundance of copper-cobalt mines in the DRC. Copper accounts for almost 70% of the primary mineral of cobalt's supply today. However, declining ore quality of existing copper-cobalt mines in the DRC limits its supply post-2030 in the base case, reducing copper's share to below 60% by 2040. Primary cobalt mines continue to take a small part, most of which comes from ASM in the DRC. Its share takes up less than 5% of the total cobalt primary supply throughout 2040 in our base case.

Nickel plays a growing role as a primary mineral for cobalt production with the rise of Indonesia's nickel production. Today, 30% of the primary mineral refined into cobalt has been from nickel plays, and this share rises to almost 40% by 2040 in our base case.

Primary resources from which cobalt is produced



Sources: IEA analysis based on Wood Mackenzie and S&P Global.

Low cobalt price threatens future production

With the weak cobalt prices persisting, mining projects are witnessing delays as project developers are forced to seek additional funding for future production. Trafigura, a commodity trading company, is now forced to seek an additional USD 200 million to USD 300 million investment, which is worth almost half the initial USD 600 million syndicated financing and marketing deal from 2022 with Chemaf SA, a mining company operating in the DRC. Had the project been completed by the end of 2023 as originally planned, the Mutoshi mine alone would have become the world's third-largest cobalt mine with capacity reaching 16 kt of annual cobalt hydroxide in its full form.

High inflation has compounded the challenges posed by the low cobalt prices. This caused the suspension of final construction of Idaho Cobalt Operations in March 2023, which would have been the only primary cobalt mine in the United States with an annual production capacity of 2 kt. The CEO of the project's developer, Jervois Global, argued that prices would have to double or additional government support would be needed to complete the construction.

Despite the unfavourable market conditions, there are some developers willing to finance new projects. Kazakh miner Eurasian Resources Group announced it would invest USD 800 million to revamp its Comide copper and cobalt mine including the construction of hydrometallurgical plant and drilling programme in October 2023. The plant is set to come online in different phases which would reach up to 15 kt of annual cobalt hydroxide output once its full capacity is met.

The weak prices also triggered actions or considerations to stockpile cobalt. China has notably taken advantage of the low cobalt price. The National Food and Strategic Reserves Administration, the government's stockpiling body, agreed to buy around 5 kt of cobalt in July 2023 and 3 kt in October. As the low price persists, there could be additional stockpiling schemes introduced from the government. The United States also reportedly considered adding cobalt to its stockpiling list. While stockpiling plans of the Defense Logistics Agency (DLA) that run from October 2023 to September 2024 ultimately did not include cobalt, the United States' efforts to diversify its cobalt supply sources coupled with low commodity price could lead to new stockpiling activities.

Smelting and refining

After mining, copper-cobalt or nickel-cobalt concentrates are obtained through mineral processing techniques including crushing, screening, drying, flotation or magnetic separation (though cobalt produced from HPAL facilities does not require significant beneficiation). Then, primary extraction using hydrometallurgical or pyrometallurgical methods take place typically close to the mines. This process produces matte, oxides, nickel-cobalt intermediates, and other co-products, which are then usually shipped overseas for further refining.

Cobalt refining continues to remain geographically concentrated in our base case. Today, China is responsible for more than 75% of the global refined cobalt supply, and its share remains at a similar level to 2040 in the base case. Finland and Japan account for around 9% and 3% of refined cobalt supply in 2023 respectively, and their shares sustain to 2040.

Among many forms of refined chemistries, cobalt sulphate used in EV batteries sees the largest increase in demand. In the base case, cobalt sulphate supply increases by more than 50% by 2030 and more than doubles in the high production case. This helps to meet the sulphate supply requirements in the APS in 2030, helped by growing secondary supply.

The role of artisanal small-scale mining in cobalt supply

The ASM sector in the DRC has historically made up a significant but variable share of global cobalt supply, accounting for an average 5-15% of the total.

The sector is highly variable depending on the price of cobalt, with higher prices incentivising more ASM activities. Due to lower cobalt prices, in 2023 ASM made up approximately 4 kt of cobalt supply, accounting for only 2% of demand. In our base case, supply from ASM increases to 7 kt in 2030 and almost 10 kt in 2040. However, as global mined supply climbs in response to demand for cobalt for the energy transition, ASM accounts for a smaller share of supply moving forward.

Due to ASM's sensitivity to market fluctuations, the sector has historically played an important role in maintaining market stability: ASM sites take much less time to begin production compared with larger industrial operations, allowing traders and producers to top up supplies during shortages or sell off volumes when other sources are in surplus. This flexibility helps to balance supply and demand, with ASM acting as swing producers. However, as ASM supplies are projected to take up a smaller share of supply moving forward, their role as swing producers may be diminished.

The sector has historically been associated with human rights abuses due to its unregulated and informal nature. Disengaging entirely from ASM as a strategy does not constitute responsible sourcing and may exacerbate the root causes of child labour. To varying extents, ASM offers socio-economic advantages; losing these may heighten the local community's vulnerability to other forms of exploitation.

There have been various efforts to formalise the sector over the years. In 2019, the DRC government created the Entreprise Générale du Cobalt (EGC), a state-owned enterprise which is intended to hold the sole right to purchase, treat, transform, sell and export cobalt extracted by artisanal and small-scale miners in the DRC. The entity released a Responsible Sourcing Standard document in 2021, outlining its steps for formalising the sector. However, the EGC has not been fully operationalised since it was established.

Formalisation of the sector could mitigate the worst forms of child labour, but could bring some unintended consequences as well. Addressing poverty at its core is essential for a lasting solution. This requires ongoing collaboration across actors and sustained community engagement.

Implications: Environmental and logistical bottlenecks mean that reliable cobalt supplies are far from assured

Environmental consequences from low-quality ores

Cobalt mining practices are becoming more energy-intensive as copper-cobalt mines in the DRC near depletion and HPAL facilities in Indonesia take on a larger role in global cobalt extraction.

As existing DRC mines edge closer to depletion, the country would have to develop new mines or dig wider and deeper in their existing open-pit and underground mines. The process of seeking better quality copper-cobalt ores would involve significant energy uses and emissions.

Moreover, the increasing cobalt extraction from nickel mines in Indonesia is raising concerns on top of the existing environmental challenges. HPAL technology uses sulphuric acid at high pressure and temperature to recover nickel and cobalt separately from low-grade deposits of nickel laterite ore. Additionally, new coal plants have often been added near HPAL facilities to accommodate an increase in power demand and provide affordable source of power to enhance the price competitiveness of mineral supply.

In recent years, there has been a notable increase of the China-backed Indonesia-based HPAL operations such as PT Halmahera Persada Lygend, PT Huayue Nickel Cobalt, PT QMB New Energy Materials and PT Huayou. In the high production case, almost half of the cobalt supply in 2040 is refined from laterite ore from today's level of less than 30%.

Cobalt mining has traditionally been supported by hydropower in the DRC, which led to relatively lower-emissions intensity associated with production. However, a combination of more energy-intensive operations in the DRC and the rise of Indonesia means that the average emissions intensity associated with cobalt production is set to rise substantially as production grows. This makes a strong case for strengthened regulatory and industry efforts to reduce emissions from cobalt production operations.

Risks of supply concentration

High concentration of cobalt mining in a single country owned and operated by foreign mining entities has shown the challenge of maintaining a secure supply. As exemplified by the recent disputes between the DRC government and foreign miners, the state's endeavour to gain more control over its mines is forming into royalty disputes and sanctions on some of the largest mines in the world.

Notably, the DRC state-owned Gécamines had suspended China-based CMOC's TFM, the world's second-largest cobalt mine, in July 2022 after an escalation in royalty dispute. CMOC holds an 80%

stake in the TFM copper-cobalt ore project and Gécamines holds 20%. The mine resumed export in April 2023 after CMOC struck a USD 2 billion deal – a USD 800 million settlement between 2023 and 2028 and at least USD 1.2 billion in dividends.

More recently in April this year, the DRC suspended nine subcontractors working at mines run by the Kazakhstan-backed Eurasian Resources Group alleging that the firms are not controlled by Congolese nationals as required by law. The sanction affects companies' operations under contracts, including Metalkol, the fourth-largest cobalt supply source in 2023.

Risks of potential supply disruptions from the world's largest cobalt supplying nation persist, amid an ongoing tug of war between the DRC administration and foreign miners over ownership stakes in the region's vast copper and cobalt resources.

Logistic constraints: Rocky roads from mines to ports

There are also risks associated with logistics due to the fragile transportation infrastructure connecting the copper-cobalt mines in Central Africa located far inland to the nearest ports, the export corridors that would ship raw minerals overseas for refining.

A large portion of DRC production currently relies on trucks to be transported over long distances by road, passing through several borders. Trucks would generally transport minerals from the so-called copper belt to Indian Ocean ports such as Beira in Mozambique, Dar es Salaam in Tanzania or Durban in South Africa, which take 17, 20 and 25 days, respectively. The road networks are inconsistent with large sections in need of significant maintenance and improvement. In rainy seasons, many roads become inoperable.

Truck deliveries have raised concerns for being more costly, slow and unreliable compared with railways. In October 2023, thousands of truckers in the DRC went on strike demanding logistics firms to pay an extra risk allowance of USD 700 per journey. The strike blocked exports of copper and cobalt produced by some of the biggest producers including CMOC's Tenke Fungurume, Glencore's Kamoto, Ivanhoe Mines' Kamoa-Kakula, and Sicomines' Mashamba West until coming to an end in November. These events related to logistics underscore that the possibility of short-term supply disruptions cannot be ruled out, even though overall supply and demand balances may appear stable.

As logistical issues disrupt secure upstream supply, railway transportation via the Lobito Corridor has gained momentum in recent years. The corridor is an agreement to construct railways and supporting infrastructure to connect mines in Central Africa to the Angolan port city of Lobito.

The United States and Europe recently announced significant financing plans for the Lobito Corridor to enhance material shipments via the Atlantic Ocean. In July 2023, the Lobito Atlantic Railway company secured a 30-year concession to provide railway services, contingent on investing USD 100 million in the DRC and USD 455 million in Angola through a public-private financing arrangement. In October 2023, the United States, the European Union, the African Development Bank, and the Africa Finance Corporation signed a MoU to co-operate on extending the Lobito Corridor, under the shared vision.

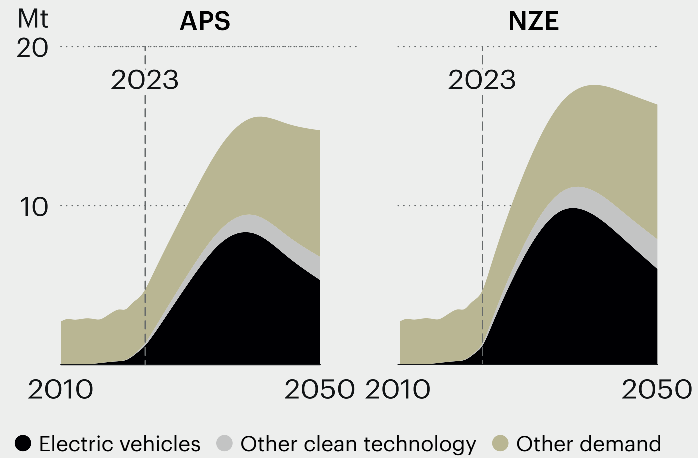
Initial trial shipments via the Lobito Corridor began in December 2023, loading copper from Kamoa-Kakula in Kolwezi and reaching the port of Lobito in just eight days. In February 2024, Canada's Ivanhoe Mines and Trafigura became the first long-term users of the corridor. Meanwhile, China proposed a USD 1 billion project to upgrade the Tazara railway connecting Zambia's copper belt to the port of Dar es Salaam in Tanzania. While the extent of the refurbishment plan remains unclear, the revitalisation of railways connecting Central Africa to both the Atlantic and Indian Oceans would help address some of the major logistical issues the region has long suffered from.

Outlook for graphite

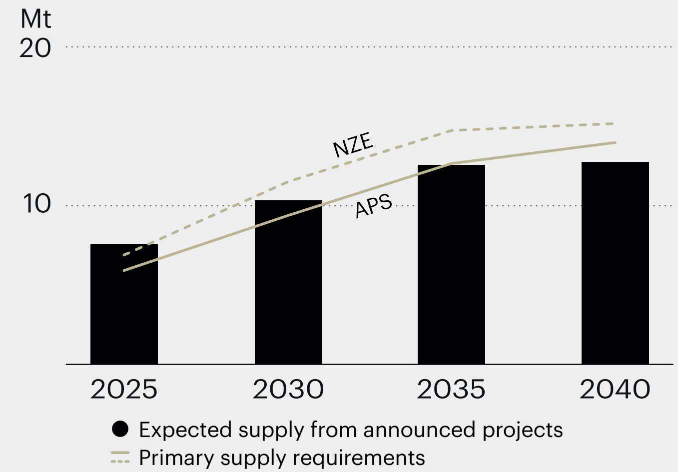
Graphite

C

Demand outlook

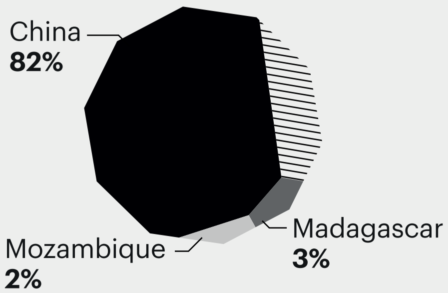


Supply requirements

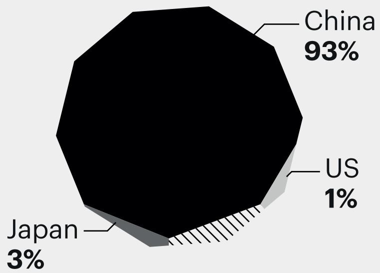


Top three producers 2030

Total supply (all grades)



Battery grade supply



Milestones (APS)	2021	2023	2030	2040
Cleantech demand (kt)	**532**	**1 292**	**6 013**	**9 839**
Other uses (kt)	3 388	3 340	4 406	6 185
Total demand (kt)	**3 920**	**4 632**	**10 419**	**16 023**
Secondary supply and reuse (kt)	149	308	1 333	2 489
Primary supply requirements (kt)	**3 771**	**4 324**	**9 086**	**13 535**
Share of top three mining countries	89%	92%	88%	89%
Share of top three refining countries	97%	98%	97%	95%

Clean energy transition risk assessment

Low Med High

Supply risks

12%

annual demand growth in the APS vs. 3% in 2010-19

Geopolitical risks

10X higher

demand than supply outside of top 1 producer in 2030

Barriers to responding to supply disruption

Limited

short-term substitution options

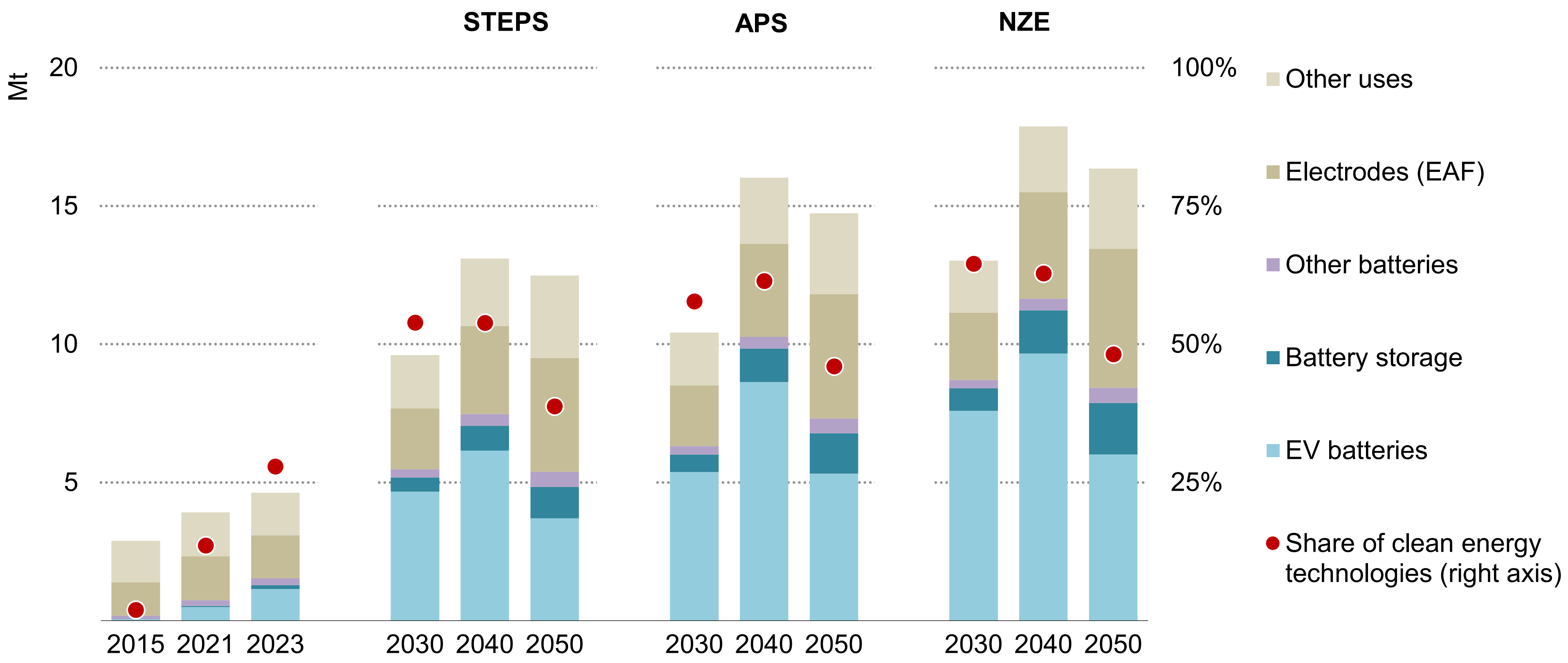
ESG and climate risk exposure

Lowest

average social and governance score for mining

Demand: Batteries are driving demand growth for graphite to 2040, with demand from electric arc furnaces for steel production also rising fast

Global graphite demand outlook by sector and scenario



Notes: EAF = electric arc furnace. Demand is for raw natural flake graphite and synthetic graphite.

Demand: As graphite maintains its dominant position in anodes, its demand is supercharged in climate-driven scenarios by the rapid deployment of EVs and battery storage

Graphite, a form of carbon commonly known for its use in pencil cores, traditionally serves various technical applications: as a lubricant, an electrical conductor, a refractory material or simply as a source of raw carbon. Historically, the metallurgical industry has been the primary consumer of graphite, employing it in crucibles, as an input for steelmaking and as electrodes in electric arc furnaces. However, the battery industry is rapidly emerging as the leading consumer of graphite, with projections indicating it may account for over half of total demand by the late 2020s.

Graphite's expanding role in battery anodes contributes to a robust short-term growth outlook, with global demand projected to double by 2030 in the STEPS. By 2040, total graphite demand reaches 13 Mt in this scenario. Meeting announced climate pledges in the APS pushes up demand further close to 16 Mt by 2040 and to 18 Mt in the NZE Scenario, a fourfold increase from today's levels.

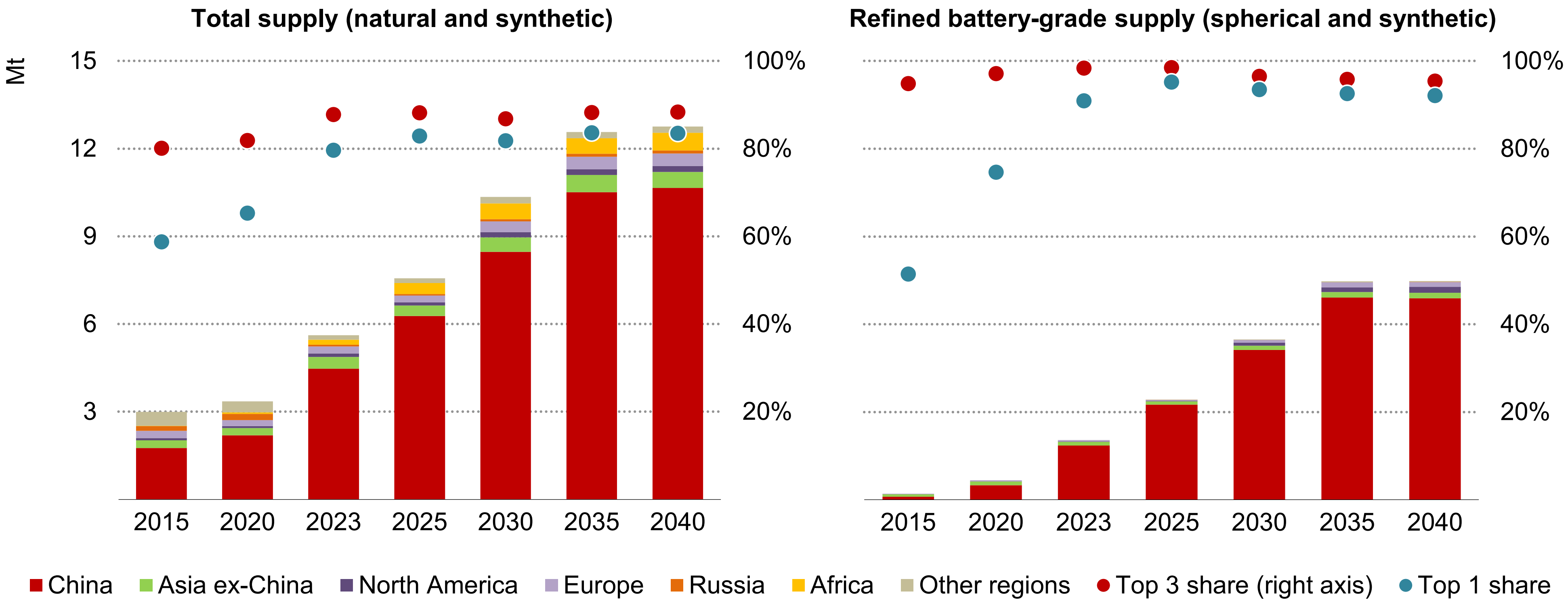
The EV industry emerges as a primary consumer of graphite. In the APS, this sector consumes 5.4 Mt in 2030, higher than current global production levels, representing 60% of total demand. Battery storage is also a significant contributor to demand growth. When considering other battery applications, such as those in electronics, the demand for graphite related to batteries – requiring specific grades and dedicated supply chains – is expected to account for 65% of total demand by 2040, compared with the 33% today.

In EV batteries, while silicon is increasingly being doped in graphite anodes, it is unlikely to challenge graphite's dominant position in the short term. However, we expect a continued shift towards higher silicon contents over time. This trend, coupled with the adoption of alternative anode chemistries such as lithium metal anodes, high silicon anodes (exceeding 50% silicon content) and hard carbon (used in sodium-ion batteries), gradually affects the pace of graphite demand growth in the longer term, leading to a moderate reduction in graphite demand in batteries post-2040. However, the speed of deployment of these alternative chemistries depends on overcoming significant technical and scaling challenges, such as ensuring high cycle life and resisting volume changes.

In both the APS and NZE Scenario, there is a notable shift towards the increased use of electric arc furnaces over traditional blast furnaces, especially in Europe, aiming to decrease emissions associated with steel production. This increases demand for graphite electrodes, primarily based on synthetic graphite. By 2040, graphite demand for metallurgical applications reaches 3.4 Mt in the APS and 3.8 Mt in the NZE Scenario, up from 1.5 Mt today.

Supply: New natural graphite mining projects emerge in diversified regions, notably in Africa, but the production of battery-grade graphite remains highly concentrated

Total and battery-grade graphite supply from existing and announced projects in the base case



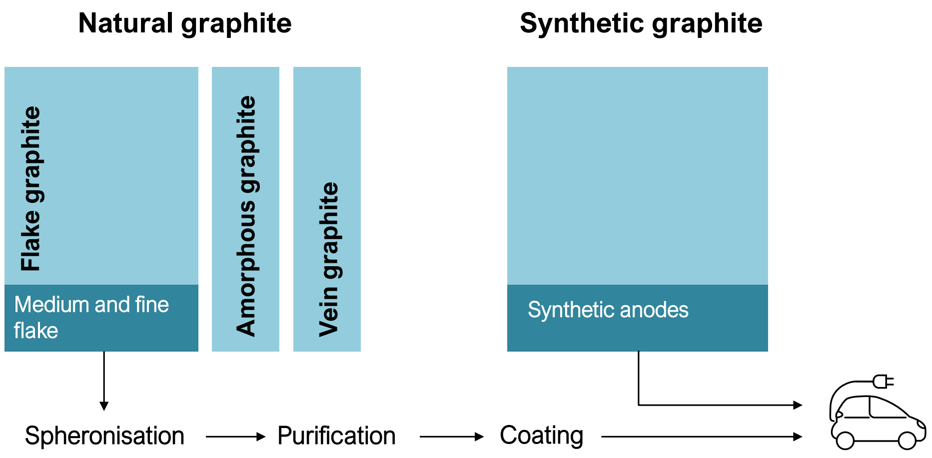
Notes: Total supply includes all grades of mined and synthetic graphite. Refined battery-grade supply includes spherical graphite made from natural flake graphite and synthetic anode production.

Supply: Options to synthesise graphite allow for sufficient supply volumes, but natural deposits are better able to support cheaper, diversified and less energy-intensive supplies

Graphite is found and extracted from natural geological deposits in various forms (vein, amorphous, flakes). However, since the turn of the 20th century and the discovery of the Acheson process, the mineral can also be synthesised from fossil fuel-based products, such as petroleum coke, with an emissions-intensive process.

Most battery producers globally are heavily reliant on China for graphite anodes. While sizeable natural graphite anode capacities exist outside of China, they depend almost entirely on refined graphite supply from China and exhibit low utilisation rates.

Battery-grade graphite supply



Mining, a limiting factor to natural anode supply

Currently, natural graphite mining is dominated by China, accounting for 80% of global production. In the base case, mined natural graphite reaches 2.7 Mt in 2030 and 3 Mt by 2040. The share of China declines to 70% in 2030 due to the growth of two emerging producers: Mozambique, notably with the Ancuabe project (60 kt), and Madagascar, with the Molo project (150 kt). Additionally, new players are emerging in Canada, India, Australia and Tanzania (Nachu project, 130 kt), aiming to cater to the growing battery market.

Not all forms of natural graphite are suitable for entry into the battery supply chain. Manufacturers use natural flakes, from medium and fine grades, and their availability emerges as a key limiting factor in scaling up battery-grade anodes based on natural graphite. The production of natural battery anodes involves multiple steps, including spheronisation, a process of reshaping the graphite flakes, involving over 50% material losses. In the base case, the need for natural graphite anode supply reaches 750 kt by 2030, and this requires close to 1 700 kt of fine- and medium-grade flakes. Of the total 2 700 kt of graphite mined in 2030, about 70% is likely to be suitable grades. This brings the battery-grade flake market slightly above equilibrium, limiting the potential for additional natural graphite supply to the battery anode market. Additional mining capacities are required to meet the necessary volumes of natural graphite anodes post-2030 in climate-driven scenarios.

Refined natural graphite: A major diversification issue

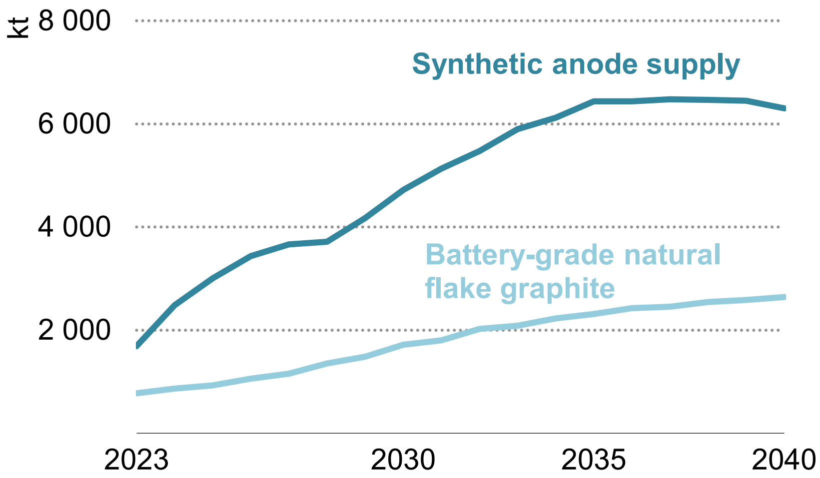
While some progress has been achieved in diversifying the mining of natural graphite, the production of spherical graphite, a refined form of natural graphite, remains highly concentrated. Currently, China accounts for 99% of the global market for spherical graphite. Although some downstream operations, such as coating and purification, are occasionally conducted overseas, industrial players in these processes become highly dependent on China for their feedstock supplies.

The industry is developing new projects in geographically diverse areas, with a growing number of integrated projects. These include Northern Graphite (80 kt) and Nouveau Monde (32 kt) in Canada, Syrah resources (38 kt) in the United States and several projects in Europe, such as Talga resources of Sweden (12 kt). If these projects come online as planned, the share of China in spherical graphite supply is set to fall to 85% in 2030 and 80% in 2040 in the base case.

Synthetic supply brings equilibrium to demand, at a cost

Due to constraints on natural graphite supply, synthetic graphite production is increasing its share in batteries although its production is also dominated by a single player, China. Synthetic graphite has been largely used for other applications, notably electrodes, which required lower-quality products. However, in recent years, battery-related synthetic graphite production has surged from zero to 40% of total synthetic graphite supply, rising to 55% by 2040. Synthetic graphite became a dominant input for battery anodes, commanding an 80% market share.

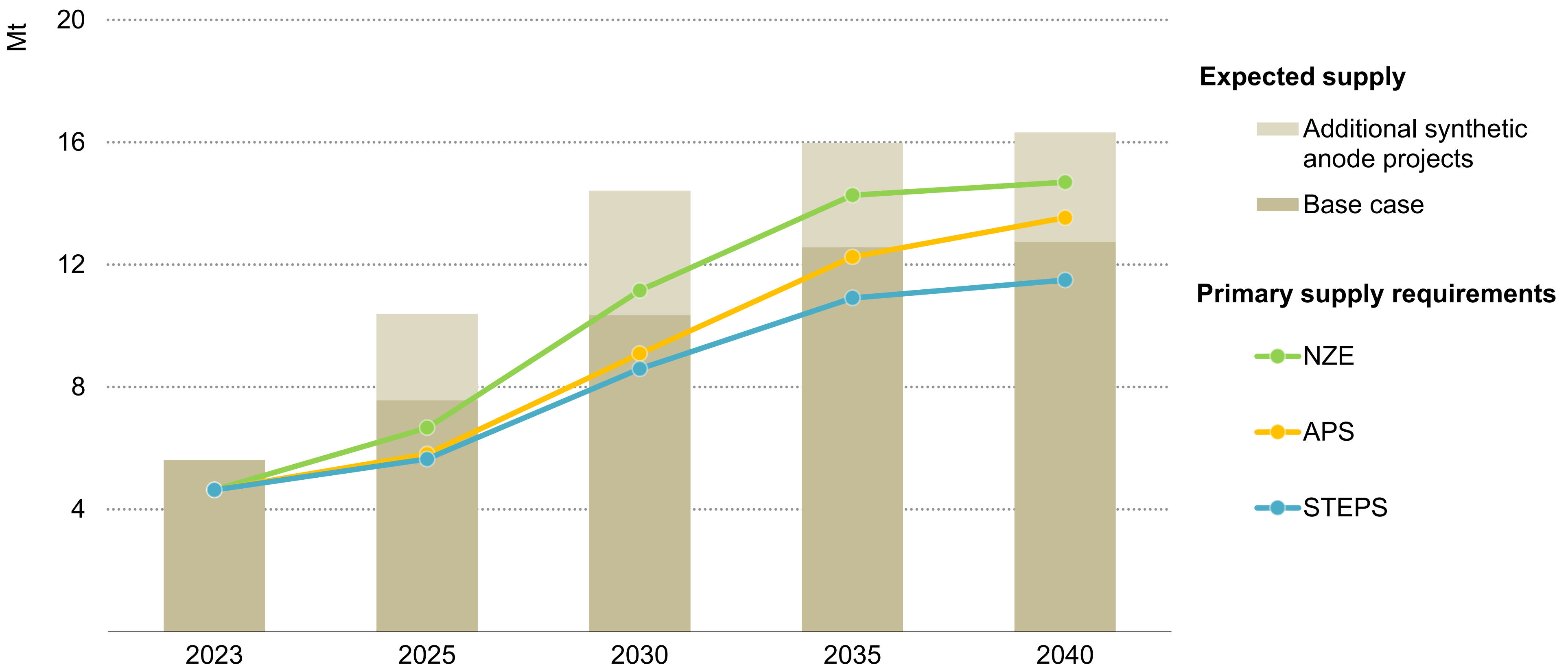
Use of mined natural and synthetic graphites in batteries



Synthesis of graphite requires the supply of needle coke, a co-product from the oil and coal industries. There are surplus capacities to produce needle coke today, mostly in China, meaning that the supply of needle coke is unlikely to be a limiting factor for synthetic graphite supply in the near term, but this may change in the long term in climate-driven scenarios.

Implications: The large pipeline of announced synthetic capacities has the potential to balance the market, although this may lead to increased supply concentration and higher emissions

Expected graphite supply from existing and announced projects and primary supply requirements by scenario



Notes: Primary supply requirements are calculated as “total demand net of secondary supply”. See Introduction for definition of the base case.

Implications: Diversification is urgently needed but faces significant challenges

In the base case, the anticipated supply of battery-grade spherical graphite and synthetic graphite is projected to be adequate to meet near-term demand. However, sustaining the long-term demand trajectory will require additional production volumes. The supply of battery-grade natural flake graphite may turn to deficits over the next decade. However, it should be noted that there is a substantial number of announced synthetic anode projects, primarily in China, exceeding the scale required in the NZE Scenario. Many of these projects are likely to experience low utilisation rates or may not come to fruition. However, this implies that any short supply of battery-grade natural graphite could result in a further increase in the share of synthetic graphite to offset the deficit.

However this comes at a cost. The extraction and conversion of synthetic graphite involves significantly higher greenhouse gas emissions compared with its natural equivalent, as it involves an electricity-intensive process relying on fossil resources. Although less energy-intensive graphite synthesis projects and techniques exist, such as lengthwise graphitisation, a higher proportion of synthetic graphite in anodes is expected to result in significantly greater GHG emissions during battery production. Nonetheless, some projects developed in areas with low-emissions power generation sources claim to achieve significant reductions in emissions compared with current supply chains.

Moreover, China currently accounts for the vast majority of existing and planned synthetic graphite production capacity. Therefore, a further increase in the share of synthetic graphite in batteries would reinforce China's dominance in this sector.

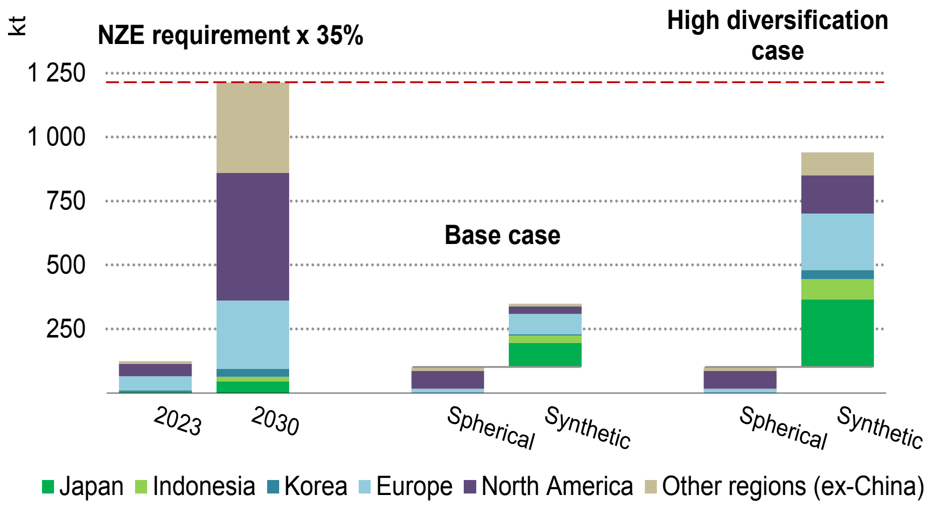
Following germanium, gallium and rare earth elements-related technologies, graphite is now subject to a system of export licences from China since December 2023. These controls specifically focus on graphite for battery grades (flake graphite, spherical graphite, high-purity products), considered “highly sensitive”, and exclude lower-quality grades, such as electrodes for metallurgical applications.

These controls can have numerous ripple effects. The announcement has placed pressure on anode producers overseas to stockpile significant volumes. As implementation commenced in January 2024, export volumes to key anode producers in Japan and Korea plummeted well below previous monthly averages before returning to normal levels in March. Customers can apply for licences with a six-month validity, a process that requires disclosure of the end user, creating significant rigidity in trade and discouraging risk-averse investors from expanding downstream capacities.

Currently, 45% of EV and storage batteries are sold and installed outside of China, translating into 350 kt of graphite content in their anodes. By 2030, this implied demand outside of China is set to reach 2.2 Mt in the APS and 3.5 Mt in the NZE Scenario. When the 35% threshold for the share of a single supplier, targeted in the EU Critical Raw Materials Act, is applied, this means that 1.3 Mt needs to come from regions outside of China.

In the base case, the expected supply outside of China falls significantly short of these material requirements. While additional projects in the early stage, not included in the base case, could narrow the gap somewhat — such as those in the United States, Korea, Saudi Arabia, India, Norway and Finland — the anticipated supply may still not be sufficient to meet the requirements. This indicates that achieving the diversification ambitions outlined in recent policy measures would be highly challenging without significant efforts to expedite the development of projects in geographically diverse regions. These projects would, however, need to move ahead amid strong competition from incumbent players and significant announced overcapacities in China, which may require strategic and co-ordinated support from governments.

Ex-China battery-grade graphite requirements and pipeline of probable projects in the NZE Scenario



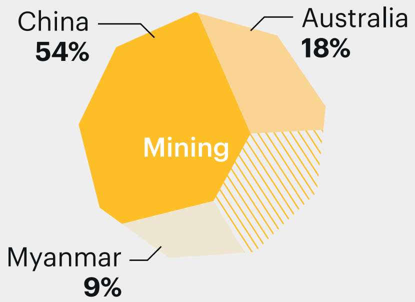
Note: High diversification case assumes that a number of early-stage projects in geographically diverse regions come to fruition.

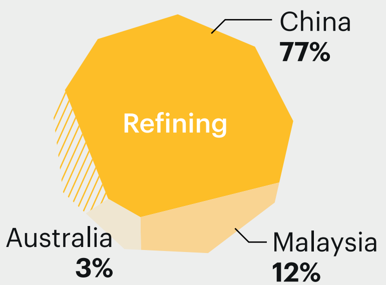
Outlook for rare earth elements

Rare earth elements

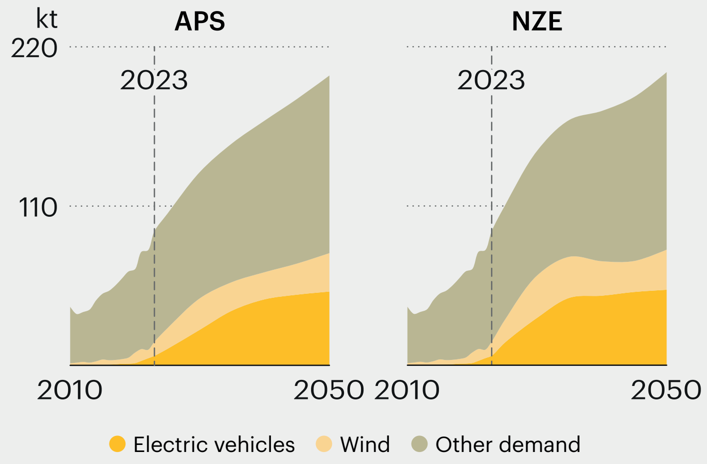
Nd Pr Dy Tb

Top three producers 2030

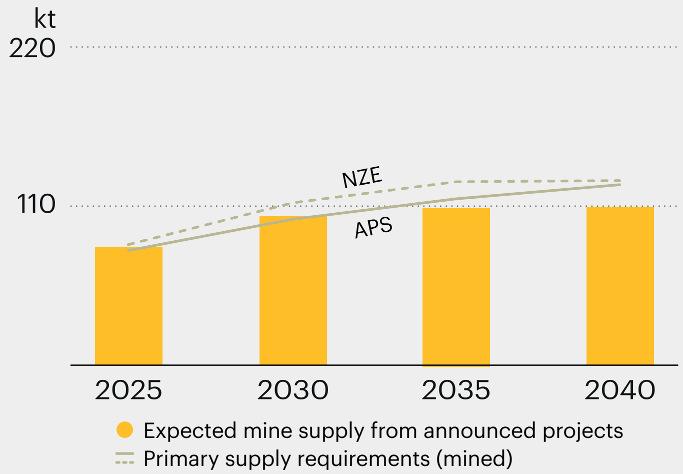




Demand outlook



Mining requirements



Milestones (APS)	2021	2023	2030	2040
Cleantech demand (kt)	**11**	**16**	**46**	**64**
Other uses (kt)	67	76	87	105
Total demand (kt)	**78**	**93**	**134**	**169**
Secondary supply and reuse (kt)	22	25	36	48
Primary supply requirements (kt)	**57**	**67**	**98**	**121**
Share of top three mining countries	81%	85%	81%	81%
Share of top three refining countries	98%	98%	92%	93%

Clean energy transition risk assessment

Low Med High

Supply risks

High
price volatility than other minerals

Geopolitical risks

77%
of refining by one single country in 2030

Barriers to responding to supply disruption

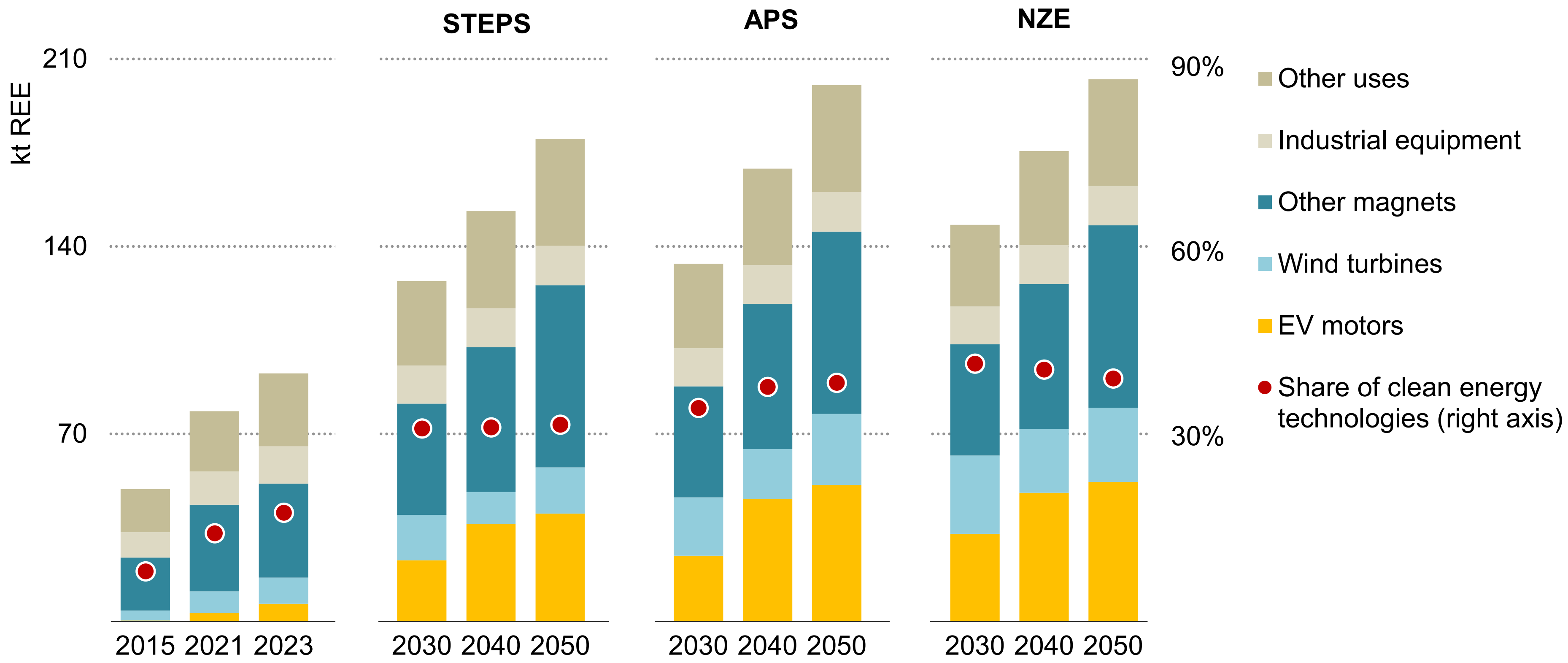
Low
transparency of pricing schemes

ESG and climate risk exposure

607 gCO_2/kWh
Among the highest average grid carbon intensity for refining

Demand: Demand for magnet rare earth elements doubles between today and 2050 in climate-driven scenarios

Global magnet rare earth elements demand outlook by sector and scenario



Notes: REE = rare earth elements. The figures are for magnet REE only.

Demand: EV motors and wind turbines drive demand for rare earth elements

Rare earth elements (REE) are a set of 17 nearly indistinguishable silvery-white soft metals. Several of these are often found together in many known deposits. Though relatively plentiful in the entire Earth's crust, they have garnered the label "rare" because of how unusual it is to find them in a pure form. Rare earth elements are usually classified into light rare earths (LREE) such as lanthanum, cerium, praseodymium, neodymium, samarium and europium; and heavy rare earths (HREE) such as gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, scandium and yttrium. Light rare earths are often used in water purifiers (cerium) and hydrogen absorbers (lanthanum) and as stabilisers in catalytic compounds (lanthanum and cerium). Heavy rare earths are used to produce more energy-efficient phosphors for the displays of computers and phones as well as fluorescent lamps (yttrium and terbium) and in fibre optic cables and repeaters (terbium).

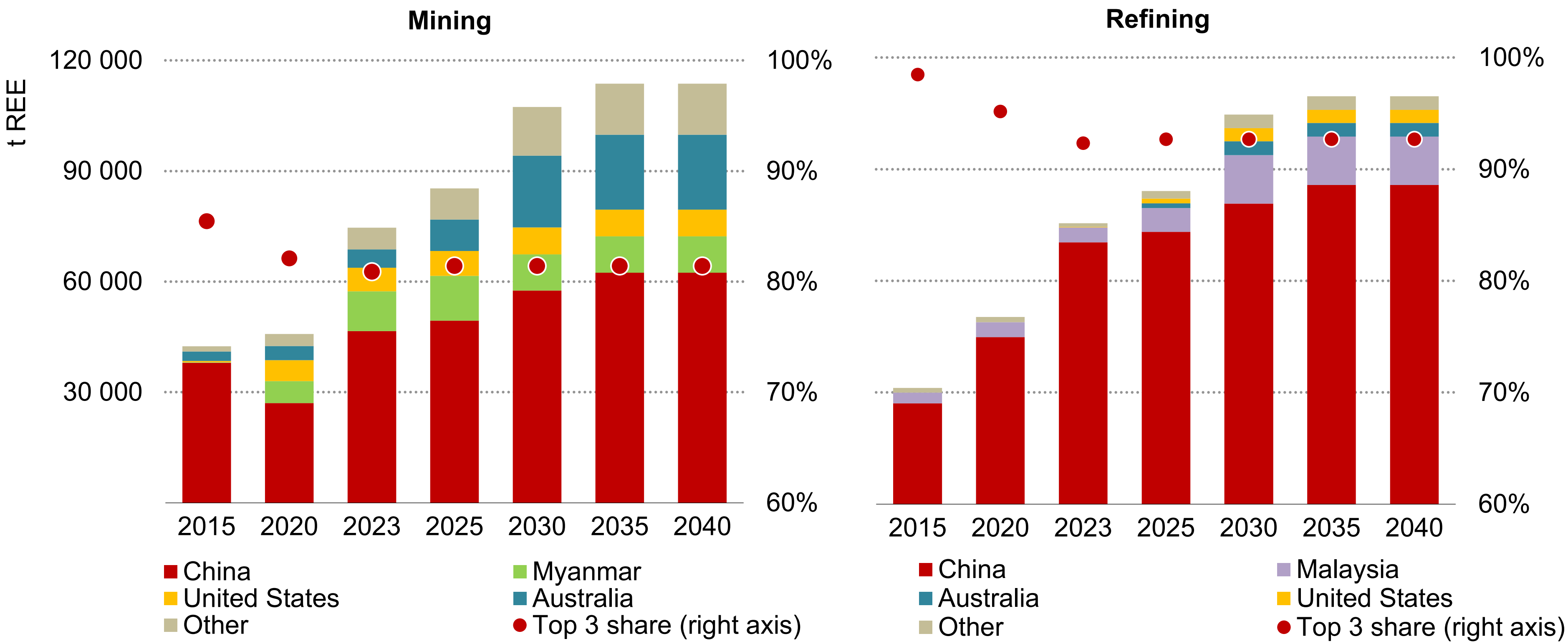
Neodymium and dysprosium can handle a greater saturation magnetisation than more common magnetic elements such as iron, which allows for fabrication of stronger and smaller magnets. Combined with other elements, these magnets (NdFeB magnets) are among the strongest magnets in the industry, able to withstand temperatures as high as 230^{0} C. This section presents analysis and insights largely focusing on the four rare earth elements that are commonly used to manufacture modern permanent magnets: neodymium (Nd) and praseodymium (Pr) are the primary elements, while dysprosium (Dy) and terbium (Tb) are commonly used as additives to enhance the performance of Nd-Pr-based magnets.

Magnets made with these elements play a very important role in clean energy transitions as they are used in automotive traction motors for EVs as well as in wind turbine motors. Electric motors and generators driven by rare earth permanent magnets represent the most energy-efficient devices developed so far, making energy savings of about 20-40% compared with ordinary motors. Moreover, the addition of small quantities (1-2 kg) of these magnet rare earth elements in a motor can dramatically reduce (60-80 kg of lithium, nickel, cobalt) the requirements for other critical minerals needed for an EV.

The global demand for magnet REE nearly doubled between 2015 and 2023 to reach 93 kt, while the share of clean energy technologies, driven by new EV sales and wind turbine deployments to meet climate ambitions, has expanded from just 8% to nearly 18% during the same period. In the APS, we see total magnet REE demand reaching 131 kt by 2030 and further to 181 kt by 2050, with the share of demand from EV motors rising most sharply from 7% in 2023 to nearly 30% in 2050. The NZE Scenario sees a slightly accelerated ramp-up of EV sales and wind turbine deployment between today and 2030 compared with the APS, driving the total demand in this year to be 15 kt higher than in the APS.

Supply: Magnet rare earths have the highest geographical concentration for refining of all energy transition minerals

Magnet REE production from operating and announced projects in the base case



Supply: Geographical concentration for mining sees some improvements om the horizon, but refining remains in very few hands

The production of rare earth elements is perhaps among the least geographically diversified of all key energy transition minerals. Their high level of geographical concentration is comparable to those of cobalt and natural graphite for mining; at the same time rare earth elements rank as the most concentrated in terms of global refining capacity. The share of the top three producers for mining of magnet REEs in 2023 stood at 85%, of which China alone accounted for 62% of global mined production. When looking at refining, the top three countries controlled the lion's share of the refined output in 2023, with China's dominance being even more pronounced than in mining as it single-handedly represented 92% of the global refined output.

The expected supply of magnet REE from operating and announced mining projects rises by 44% and 52% respectively from today's levels to surpass 107 kt in 2030 and reach 114 kt in 2040. The dominance of the top three countries in global mined supply reduces slightly, falling to around 81% of the total compared with 85% today. The expected refined supply from operating and announced projects rises similarly to 106 kt in 2030 and over 110 kt in 2040, with the share of top three refining countries remaining extremely high, falling marginally from 98% to 92% today. By 2030, China's share of global refined output falls to 77%.

The type of ores that the four magnet REE often come from is heavy sands (monazite sands), which also contain radioactive elements such as uranium and thorium, making their extraction quite challenging. Outside of China, very few countries have the infrastructure and the willingness to build solutions for the storage of these radioactive by-products. Processing a kilogramme of rare earth oxides can produce close to 1 kilobecquerel of uranium-235 (U-235) equivalent of radioactive elements. Proper storage is the only way to prevent this material from entering the environment through waste streams, but studies show that only 17% of operating rare earth miners align with the Global Industry Standard on Tailings Management (GISTM). Appropriate waste management performance will be vital to scaling rare earths supply chains in geographically diverse regions.

In the upstream segment, only a handful of mines are operating at scale outside China and Myanmar (one each in the United States, Australia, Viet Nam and Brazil), and some mines are producing the rare earths as a by-product of manganese or titanium production. In general, newly announced projects have a lead time of eight years on average, making the scaling up of mined production beyond China a challenging proposition. The refining segment of the supply chain outside China is even more nascent than mining, with only a couple of operating industrial-scale facilities existing in Malaysia and Estonia, some facilities in Australia nearing operation, and some smaller-scale refining units nearing operation in France and the United States.

Regional mining trends

On mining, a vast majority of total mined REE production as of 2024 comes from China, notably from the Bayan Obo mines in Inner Mongolia. In the rest of the world, Mount Weld in Australia and Mountain Pass in the United States are leading producers. The two fastest growing regions in terms of mined production of magnet REE between 2015 and today have been Myanmar, which grew its share in global production from just 0.2% to 14%, and the United States whose share grew from 1% to 9% in the same period. In the period to 2030, China remains the top mining country for magnet REE supply, but Australia increases its share in the global total to 18% and the United States maintains its share similar to today's levels at 7%.

REE mining in Myanmar

Most REE mining operations in Myanmar occur close to the Pang War-Tengchong border crossing with China in Kachin State, which is largely controlled by the Kachin Independence Organisation (KIO). As a result of the proximity of these critical resources to China, the vast majority is transported over the border for further processing and refining. While most tin concentrate sourced from Myanmar is processed in Yunnan Province, China, it should be noted that REEs sourced from Myanmar are far more difficult to trace. This is a result of the multiple REE processing facilities throughout China that often combine raw materials from diverse sources. The resilience of all global supply chains was tested during the pandemic. During this period, the trade of both tin and REEs from Myanmar to China was negatively impacted by major border port closures, notably at the Menglian, Diantan and Menglong ports, resulting from China's zero-Covid policy, exposing the existing fragility of this supply network.

In April 2023, the KIO announced the suspension of REE mining in Kachin state from 4 September 2023, as protests highlighted environmental damage from mining and processing. Despite this, Chinese companies were permitted to gradually halt production in line with necessary steps rather than coming to an abrupt halt. Pressure has been building to comprehensively monitor mining operations in the region following environmental concerns, with the local government announcing inspections of REE mining operations in September 2023 that were expected to last only ten days, equating to one to three weeks of supply. However, after random inspections across more than 300 mining sites, the extended suspension has led to the temporary dismissal of local workers and uncertainty surrounding the resumption of operations as no new notices have been released by authorities.

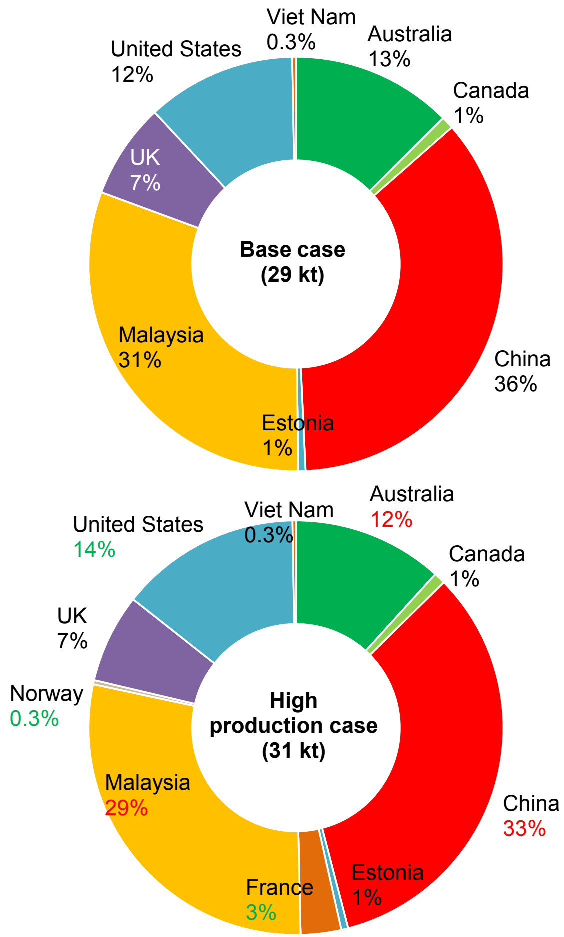
Chinese imports of REE material spiked significantly in August 2023, increasing by approximately 76% year-on-year, according to Chinese trade data, prior to the implementation of the suspension. Stockpiling of REE material ahead of peak consumption was further driven by environmental inspections that took place in late August in Jiangxi province, a major REE production hub. In early 2022, REE manufacturers in Ganzhou, Jiangxi province, suffered production capacity reductions of at least 25% after border gates between Myanmar and China were shut down at the beginning of the year, illustrating the significance of the current suspension.

While reserves should be sufficient for up to three to six months, any extended suspension of REE mining in Kachin state could be damaging for refineries in China reliant upon feedstock from Myanmar. The government-guided price for REEs in China has remained relatively low to incentivise downstream production, as magnet producers have found it increasingly difficult to pass additional costs to downstream end users, though this has caused poor financial performance for upstream operators.

Regional refining trends

On refining, Chinese dominance in 2023 remained unchallenged. In the rest of the world, refineries owned by Lynas in Malaysia, Viet Nam Rare Earth JSC (VTRE) in Viet Nam and Neo Performance Materials in Estonia (Silmet) are the few notable industrial-scale producers. The fastest growing region in terms of refined production of magnet REE between today and 2030 is Malaysia, raising its share in global

Additional refined output of magnet REE between 2023 and 2030 in the base and high production cases



Notes: The shares in the figure indicate share of additions to 2030 and not the absolute share of the country in global refining capacity. UK= United Kingdom.

refined output from 5% to 12%. While the overall picture for regional distribution of expected refined supply does not change much to 2030, there is an additional 29 kt of refined output between 2023 to 2030 in the base case and 31 kt in the high production case. The majority of additions to 2030 in the base case come from China, Malaysia, the United States and Australia. In the high production case, the emergence of France and Norway as refiners in Europe reduces China's contribution to the total additions to 2030 by 3 percentage points.

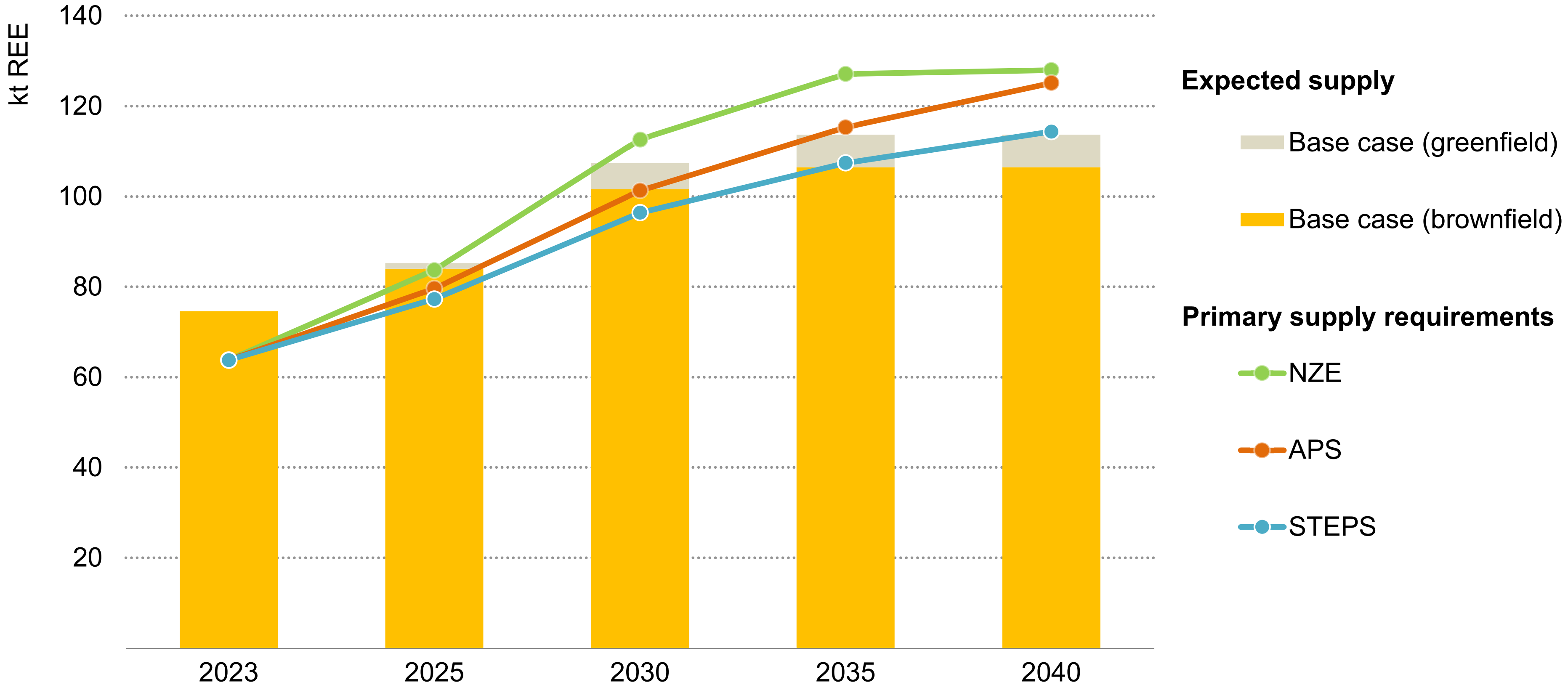
REE refining in Malaysia

Lynas' operation in Malaysia from 2012 made it the first REE refining plant outside China. After years without steady supply of REEs, Japan started sourcing the materials from Malaysia since 2013 – which has enabled Japan to recover and increase their manufacturing activities since then. Currently, Lynas produces rare earth oxides, carbonates, oxalates and chlorides in Gebeng, Pahang, with a total capacity of 22 000 tonnes per year.

Recognising the potential of the downstream industry of magnet manufacturing as well as the advantages of having rare earth oxides (REO) production as raw materials in the country, the Malaysian government, through the Malaysian Investment Development Authority (MIDA), has been promoting the production of advanced materials including rare earth magnets under the Promotion of Investment Act (PIA) 1986. To continuously support this, MIDA announced that it will continue its collaborations with the relevant stakeholders to attract potential investors to develop the industry. The support will focus on downstream manufacturing activities, as well as integrated projects including rare earth metals manufacturing that can convert oxides into metals.

Supply: Expected supply nearly in line with requirements to 2030, but limited announcements of new projects with long lead times pose risks

Expected mined magnet REE supply from existing and announced projects and primary supply requirements by scenario



Notes: Based on mined output. Primary supply requirements are calculated as "total demand net of secondary supply", also accounting for losses during refining operations. See Introduction for definition of the base case.

Implications: Supply risks arise from challenges to diversification of production

Demand-supply balance and secondary supplies

For the four magnet rare earths mentioned above, the supply from today's operating projects is sufficient to meet current demand, and this is broadly likely to be the case in 2025. Between 2025 and 2040, the majority of the supply increases come from operating mines, particularly Bayan Obo in China and Mount Weld in Australia, increasing their expected production (brownfield expansion). The primary supply requirements (total demand net of secondary supply) in the STEPS grow in line with the projected brownfield and greenfield expansion and can be satisfied if additions occur as planned. However, after 2025, for the NZE Scenario and 2035 for the APS, a gap emerges between projected primary supply requirements and supply additions. In the NZE Scenario, there is an implied supply gap of 5 kt in 2030 and 14 kt in 2040. The major concern for magnet REE, however, is not a huge gap between demand and supply like in the case of copper or lithium, but rather an extremely important level of geographical concentration of today's as well as future mining and refining projects that expose this market significantly to supply disruptions.

Primary supply requirements in the medium to long term are also a function of growing interest in recycling manufacturing scrap and end-of-life magnets that will generate secondary supplies. In 2030, around 35 kt and 40 kt of total magnet REE demand may be met using secondary supplies respectively in the APS and the NZE Scenario. Between 2030 and 2050, the secondary supply expands 1.7-fold in each scenario, to 60 kt and 67 kt respectively. Recycling so far has focused on the traditional "long-loop" recycling, which involves breaking down each element using various techniques to recover them as rare earth oxides that then have to be converted into metals before being cast into alloys and broken down into a fine alloy powder to make the magnets. It is an important but energy-intensive and expensive process. New technologies such as those of HyProMag, a UK-based company with its recycling facility in Birmingham, and MagREEsource, a French start-up that secured Euro 5 million to open its pilot site in Grenoble, have recently been in the news for their patented Hydrogen Processing of Magnet Scrap (HPMS) technique, which uses hydrogen as a processing gas to separate magnets from waste streams as a magnet alloy powder, which can be directly compactified into sintered rare earth magnets. This "short-loop" process does not require heat and is relatively quick, and magnets made with these recycled elements have been shown to have significantly lower enviromental footprint (CO_2 emissions and water consumption) than those produced in China from mined minerals. Other companies using innovative recycling technologies, such as ReElement Technologies in the United States and Ionic Technologies in Northern Ireland, receiving support from major companies provides further positive signals for increasing contributions from secondary supplies.

Project funding grows steadily despite price declines

Two major rare earths producers outside China, Australia-based Lynas Rare Earths Limited and US-based MP Materials Corp., are clamping down on costs to offset a sharp drop in prices and weak Chinese demand. Lynas' average selling price for neodymium-praseodymium (Nd-Pr) fell by 32% per kilogramme year-on-year between July and December 2023, while MP Materials witnessed a 34% price dip to USD 5 622 per metric tonne of rare earth oxide concentrate year-on-year for the December 2023 quarter. This low-price environment in recent months, in part caused by China producing in excess of demand, has created some tensions in the market, but many experts believe that long-term demand beyond 2025 will remain robust. Industry expectations are that export credit agencies will continue to support rare earth developers outside China, despite the challenging price environment at the moment. Moreover, China will continue to be a strong driver of rare earths demand, as evidenced by China's BYD Company Ltd. overtaking Tesla Inc. as the top-selling EV maker in 2023. Under these circumstances, China may prioritise supply for the domestic market, leaving a deficit globally.

Since the last major global discussion about potential disruptions in rare earth elements supply in 2011, almost no new large-scale facilities have come online. The feasibility of announced projects for these minerals has been very low outside China. Efforts for diversification can be seen from different parts of the world. In September 2023, the Malaysian government stated that it is considering a ban on unprocessed rare earth concentrate in order to boost domestic REE processing. In March 2024, it was further mentioned that the Malay National Mineral Council would assess a proposal to create a government-linked company for rare earth extraction. In the United States, USA Rare Earth (USARE) signed an offtake agreement with ReElement Technologies in March 2024 for supply of rare earth oxides to its magnet manufacturing facility in Oklahoma from 2025, with the goal of expanding to 900 tonnes per year by 2028. Additionally, the US Export-Import Bank sent letters of interest in March 2024 to provide up to USD 600 million in debt funding to rare earth developers Meteoric Resources and Australian Strategic Minerals. Meteoric Resources is developing the Caldeira project in Brazil targeting ionic adsorption clays, while Australian Strategic Minerals is developing the Dubbo project in Australia and downstream metallisation capabilities in Korea. This announcement from the United States follows a series of government backed investment in rare earth projects, with the US Department of Defense providing additional funding to Lynas Rare Earths for its Texas-based refinery, and the Australian government providing financial support to Hastings Technology Metals, Iluka Resources and Arafura Resources to continue development of their respective rare earth mines and processing facilities.

There are two broad classifications of magnets made from REE: bonded magnets (smaller magnets, mainly used for electronics or small motors) and sintered magnets (most commonly used in traction motors for EVs and wind turbines). Besides China, only two facilities in Japan are known to produce the latter at industrial scale. New project announcements from Neo Perfomance Materials in Estonia approved by the European Commission and some from the Korean company Star Group funded by POSCO could come online within the next years. Roughly, three-quarters of the unit cost of making permanent magnets is attributed to the raw materials and about 10% to energy costs, and the rest is labour costs. Labour costs (not labour intensity) are comparable to China in Europe and North America; however, energy costs are significantly lower in China. Today, original equipment manufacturers (OEMs) are hesitant to pay the 30% premium – equivalent to around USD 30 to USD 50 per vehicle – that comes from energy costs and trade taxes for magnets made outside China, creating the biggest challenge for diversification of the industry in the rest of the world.

New technologies: Innovative extraction processes and new magnet technologies

There is a constant development of new rare earth processing technologies by various industry participants globally, though many of these processes have struggled to make significant advances. This is not always the fault of the technology developer, however, with difficulties in acquiring necessary feedstock at commercially viable prices, as is the case for REEtec in Norway, also causing delays and setback at processors.

Will ionic adsorption clay deposits change the game?

Ionic adsorption clay (IAC) is also known as regolith-hosted ionic adsorption deposits (IADs), which contain rare earth elements adsorbed physically to the clay minerals surface, mainly kaolinite and halloysite. Weathering of igneous rock, primarily granite, that contains specific rare earth-bearing minerals results in the formation of IAC. The best environments for this process to occur are warm, humid and slightly acidic conditions in subtropical regions. Important source rocks typically have a relatively high background in rare earths and rare earth-bearing minerals in these rocks will include monazite, xenotime, bastnaesite, allanite, titanite and apatite. The hype surrounding this form of deposit comes from the hope that extracting rare earths that are loosely bonded to the surface of rocks is relatively simpler, less energy-intensive and cheaper than obtaining them from the depths of hard rock formations, and could also avoid the radioactive by-products that accompany the traditional mining processes for these minerals.

Ore deposits containing physically adsorbed lanthanides are substantially lower-grade than other rare earth deposit types (hard rock); however, the low mining and processing costs make them economically attractive as sources of rare earths. Global resources of HREE are dominantly sourced from Chinese regolith-hosted IADs or clay deposits in Myanmar and Laos, in which the elements are inferred to be weakly adsorbed onto clay minerals. Similar deposits elsewhere might provide alternative supply for these high-tech metals, but the adsorption mechanisms remain unclear.

Traditional REE projects based on hard rock developments are extremely capital-intensive and can cost USD 1 billion to USD 2 billion to build, for which most junior miners cannot secure funding. In recent years, focus in the junior miner space has shifted from highly capital-intensive hard rock REE projects to low capital-intensity IAC projects which are enriched in HREE. Despite in-situ grades being lower than most hard rock projects, the mining is easier, leading to substantially lower capital expenditure and operating costs. Most clay operations involve digging or scraping of only the top twenty metres or so of earth, as opposed to blasting hard rock sources which may extend down to hundreds of metres or more. Clay material is soft and requires only breaking up, whereas hard rock material needs to be crushed and ground, often in large quantities. Then there is the processing. Large-scale high temperature roasting and acid leaching for hard rock projects, compared with heap or vat leaching at atmospheric temperature and pressure for ionic clay projects. Last but not least, clay waste material is generally inert and can be backfilled into the mining area, meaning there is no need for tailings dams or dry stacking.

In regolith deposits, Chinese miners found that weakly acidic ammonium sulphate or sodium chloride solution readily reclaims the rare earths from the ionic bonded clays, allowing the resulting crude solution to be chemically treated to eliminate contaminants for further solvent extraction separation and refining. This processing can be in-situ leaching; heap leaching; or in-tank leaching with increasing cost and all with significant environmental impact. Generally, Chinese costs for REE reclamation from IAC deposits are low and despite the low recoveries peaking at around 30% to 40% in final products, these projects appear to be economic.

The economic viability of IAC deposits remains uncertain, but they look increasingly attractive from perspectives of capital intensity, ease of working, carbon intensity and radioactive waste management. While China appears to have developed a low-cost method of reclaiming rare earths from IAC deposits, not all REE clay projects are IAC projects and it is important for prospective investors to have sufficient metallurgical testing carried out to establish the ionic adsorption capacity and suitability for ion exchange within all new clay discoveries.

There has been a steady flow of announcements of IAC discoveries outside southern China and Myanmar in recent years, such as in Australia, Brazil and Uganda. How quickly these discoveries can be converted to projects operating at scale remains to be seen. In March 2024, Appia Rare Earths & Uranium announced a maiden mineral resource estimate for its ionic adsorption clay PCH project in Goiás, Brazil.

In addition to the growth in IAC type production, the most significant change in the rare earth space would be the growth of supply from heavy mineral sand (HMS) operations, which are expected to contribute volumes of not only Nd-Pr feedstocks but also provide notable quantities of Dy-Tb to downstream processors. While some HMS producers are looking to integrate production, as is the case with Iluka, Energy Fuels and Tronox, many producers will continue to supply material into the Chinese market.

Alternative magnet technologies

On the technology innovation side, the development of alternative magnet technologies such as iron nitride has been a key topic of interest for many stakeholders wanting to understand the potential impact on neodymium iron boron (NdFeB) magnets used in automotive applications. Niron Magnetics' Clean Earth Magnet has attracted interest from General Motors in the United States, with whom Niron has partnered for the development of EV drivetrains, starting with a demonstrator for the Chevrolet Bolt. Further funding for Niron has also come from Samsung and Stellantis.

One apparent disadvantage of iron nitride magnets is that their coercivity is less than that of neodymium. Coercivity is a measure of the magnet's ability to resist having the polarity of its field reversed when exposed to a strong opposing field. Without coercivity, the magnetic fields in a motor would rotate without turning the shaft. Initial assessments indicate that iron nitride will struggle to compete with incumbent neodymium iron boron magnets for automotive drivetrains as the importance of high magnetic density, high coercivity and field strength which the latter technologies bring are non-negotiable for compact motor and EV manufacturers.

Brief review of other key materials

Aluminium

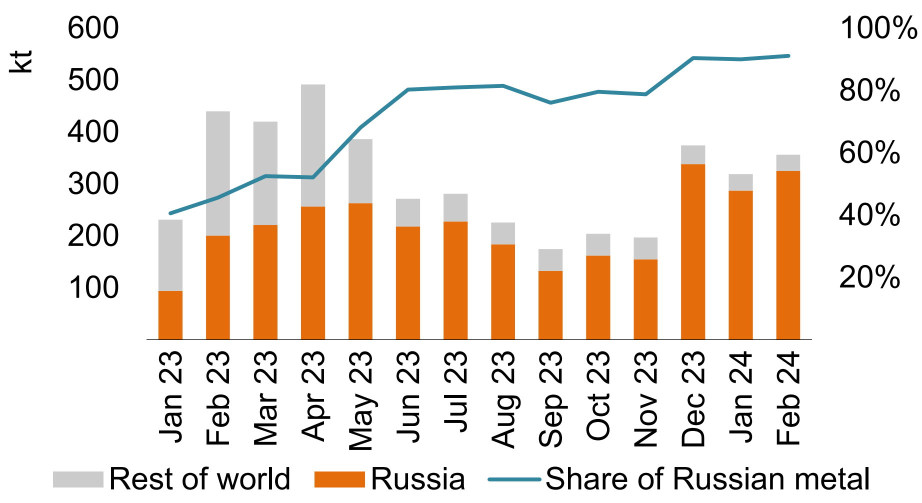
Aluminium traded within a fairly narrow range of USD 2 100 to USD 2 450 per tonne over the past year, with the strong dollar and slowing industrial activity setting a ceiling on prices. This trend is likely to continue in the near term owing to the persistent slowdown in manufacturing as well as supply-side uncertainty. In the long term, global demand growth is expected to narrow the surplus, driven in large part by increasing utilisation in clean energy applications.

Aluminium's use as a lightweight structural element in solar PV installations and EVs is expected to remain as a primary demand driver. In addition, transmission requirements arising from increased electricity demand and renewable penetration are expected to boost the use of aluminium conductor steel-reinforced cables. Demand growth from traditional demand sectors in construction and manufacturing are likely to remain modest.

On the supply side, drought risks in the southwestern Chinese province of Yunnan pose significant near-term potential for supply volatility and elevated prices. Hydro-powered Yunnan accounts for about 12% of Chinese aluminium production, but low water levels have resulted in production cuts totalling more than 1 Mt per annum between November 2023 and February 2024.

The proportion of Russian metal within LME stocks has doubled from 45% in February 2023 to over 90% in 2024 amid low overall stock levels. The LME's April 2024 ban on accepting Russian aluminium, copper and nickel created opportunities for traders, which further dried up the liquidity for tradeable metal.

Proportion of Russian metal within LME stocks

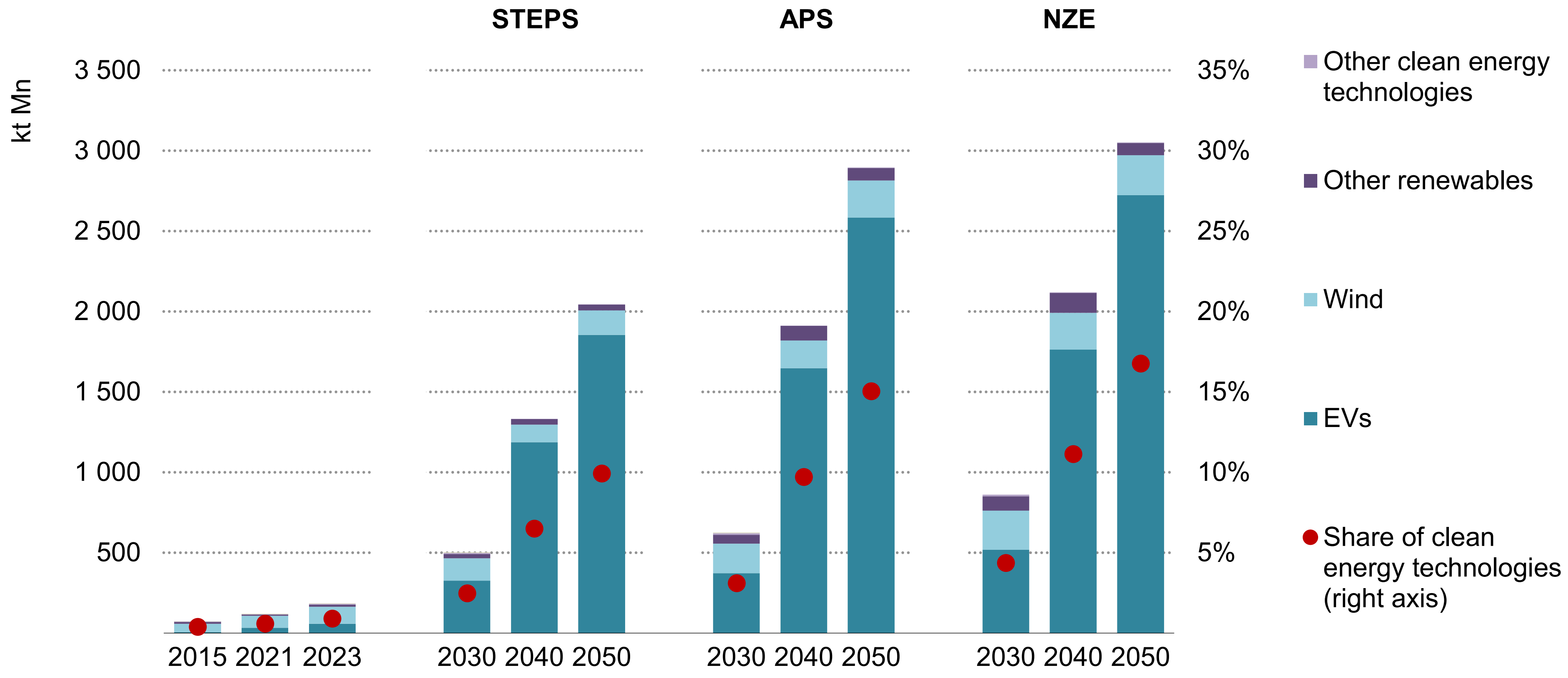


Source: IEA analysis based on London Metal Exchange.

Global production levels are expected to be able to serve near-term demand increases. Despite slowing growth in China as primary production capacity reaches the government-mandated limit of 45 Mt per year, secondary production growth as well as new smelting capacity are expected to support long-term market growth.

Manganese: Demand surges driven by EV batteries, but significant concerns remain about the future supply of battery-grade manganese sulphate where China dominates supply

Manganese demand in clean energy technologies by scenario



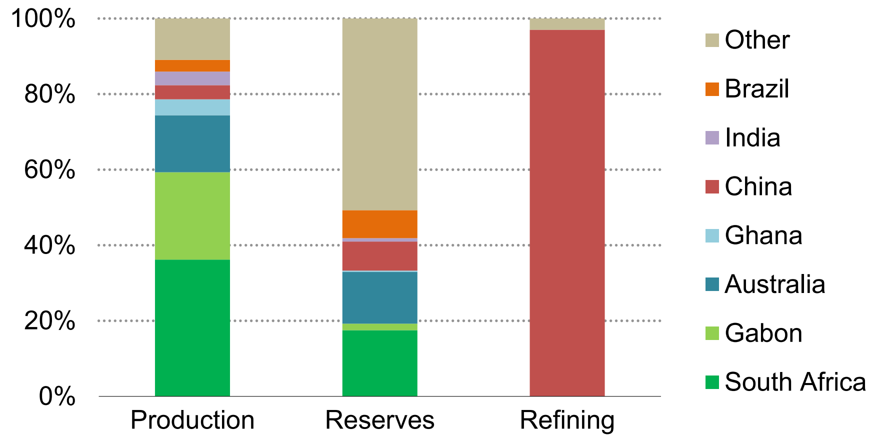
Source: IEA analysis based on US Geological Survey (2024), Minerals Commodity Summaries 2024.

Manganese

Manganese demand is primarily driven by steel, as it is a key component of steel alloys. Currently, batteries account for a small share of total manganese demand; however, this share is set to increase rapidly due to the surging deployment of EVs. Manganese is a critical component of one of the dominant EV cathode chemistries, NMC, as well as now being utilised in the new variant of the current leading chemistry LFP known as LMFP, where LMFP is set to start taking market share. For instance, CATL's LMFP cells have been confirmed for use in six models in China and are undergoing validation by Tesla, who are expected to use the cells in the Model 3 made in China. The addition of manganese increases energy density compared with traditional LFP. Other chemistries under development such as lithium nickel manganese oxide (LNMO) also use higher fractions of manganese compared with conventional nickel-rich cathodes. Therefore, this shift towards greater manganese contents in cathode chemistry is expected to drive a surge in demand. Manganese is also a key metal used in wind turbines as a critical part of steel components.

By 2030 manganese demand from clean energy technologies increases almost threefold in the STEPS, over threefold in the APS and almost fivefold in the NZE Scenario. By 2050 manganese demand from clean energy technologies is a remarkable 11 times higher than today in the STEPS, 16 times higher in the APS and 17 times higher in the NZE Scenario. The rapid growth in EV deployment is responsible for the exceptional increase in manganese demand in clean energy technologies. This results in the share of demand from clean energy technologies increasing from 1% today to 15% in 2050 in the APS and 17% in 2050 in the NZE Scenario. Thus, steel remains the dominant driver of total manganese demand. However, it is critical to note all of this remarkable growth in manganese demand from EV batteries will need to be high-purity manganese sulphate.

Geographical distribution of manganese production and reserves



Note: Refining refers to production of battery-grade manganese sulphate.
Sources: US Geological Survey (2024), Minerals Commodity Summaries 2024 and IEA (2023), Critical Minerals Market Review 2023.

In terms of supply, mined manganese production is highly concentrated with the top three countries producing three-quarters of global supply. South Africa is the world's largest producer with 35% of production, followed by Gabon with a quarter and Australia with 15%. This concentration already poses significant risks. Exports of manganese ore from Gabon dropped by 13% from 2022 to 2023 due to the military coup and a landslide on key rail infrastructure which required significant maintenance. This increased political instability and risk deters investment and causes concern for future supply disruptions for the key supply region. Gabon also has the highest grade (average 45%) compared with the other two leading producers Australia (42%) and South Africa (38%), thus its critical importance for global manganese supply. Australia's GEMCO mine is the world's second-largest manganese mine but it has suspended exports due to infrastructure damage from Tropical Cylone Megan in March. Operations and export sales will remain suspended until early 2025. Exports from South Africa also dropped by 7% following extreme weather, maintenance challenges and insufficient investment for key rail infrastructure transporting manganese ore.

Nevertheless, there is potential for diversification, seen by comparing current production with reserves (defined as economically extractable resources). In terms of reserves, South Africa is indeed the largest with almost 20%, followed by Australia with 15% of the global total. China and Brazil hold significant reserves with 15% together. There are several qualifications which must also be taken into account when assessing reserves including the resource quality or any above-ground constraints limiting potential. Also, critically, there is a need for updated geological surveys in emerging and developing economies, where the current surveys are out of date.

However, the critical risk for manganese is the supply of high-purity manganese sulphates required for battery chemistries, a crucial issue given the remarkable growth from EV battery demand. While manganese is abundant, only around 1% of global supply is suitable for batteries. China dominates supply of battery-grade manganese sulphate, producing 97% of global supply. There are only two other refineries outside China in operation, in Japan and Belgium, though with several projects in development including in Canada, South Africa, Australia and the United States. With manganese sulphate prices relatively low due to slight surpluses from China, it is difficult for many other regions to compete with China on costs. This is proving challenging for new ventures to be competitive and secure investment. Some analysts even forecast a deficit in supply of battery-grade manganese sulphate as early as 2027, adding concern for ensuring sufficient supply for EV batteries. Nevertheless, the total dominance of China in the supply of high-purity manganese sulphates today is a major risk alone, making supply highly vulnerable to suddent changes in policy, geopolitics or supply shocks.

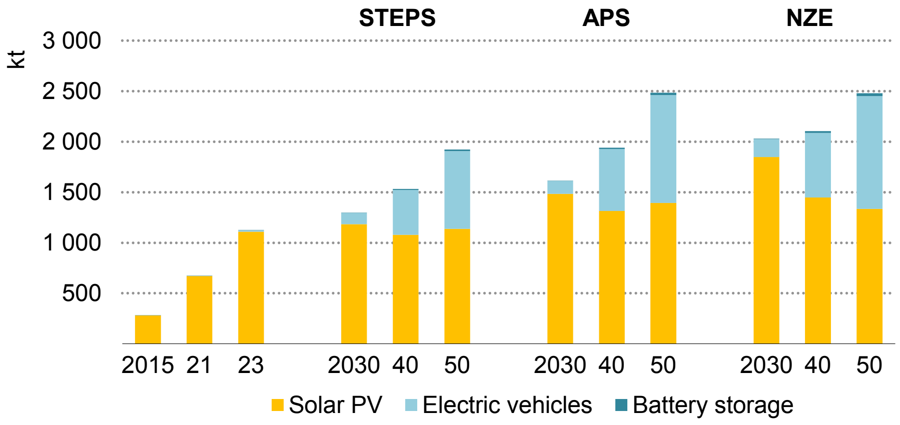
Silicon

The silicon market is poised to be affected by two waves of demand growth from clean energy technologies. A first phase is related to the ramp-up of solar PV deployment, requiring close to 1.5 Mt in 2030 in the APS, and close to 2 Mt to meet the needs in the NZE Scenario. A second phase corresponds to the growing use of silicon in the battery industry, as a higher-performance substitute for graphite, with related demand reaching over 1 Mt in 2050 in the APS and the NZE Scenario.

Silicon is produced in its metallic and crystalline forms using silica-rich minerals, generally from high-purity quartzite. The existing silicon industry is already mature, supplied by an abundant resource, with a current global production already close to 3.8 Mt, but new demand trends related to clean energy (and also digital transitions) are transforming the supply chain, requiring larger volumes of higher-purity products. Consumption was historically dominated by the aluminium alloy industry and silicone producers (silicon-based polymers, often found in rubber or oil-like products), calling for "metallurgical grade" of 99.99% (4N) purity silicon. Solar PV is known for requiring 99.9999% (6N) while electronic applications can require even higher purity, ranging up to 11N. Both electronic and solar PV uses may increase demand for high-purity products.

Technological gains in efficiency are significantly reducing pressures on silicon resources, with requirements in solar panels declining from 6.8 g/W in 2010 to 2.3 g/W in 2022 and close to 1.5 g/W in the latest generation of solar PV technologies.

Silicon demand related to clean energy technologies by sector and scenario



For EV batteries, manufacturers are already adding small volumes of silicon in anodes, but further increasing this share faces significant technological hurdles, such as swelling during the charging cycle. Several start-ups are developing various silicon nanoproducts to reduce these effects, suggesting potential for new specialised silicon supply chains. For stationary storage, silicon uses are expected to remain small, due to lower energy density requirements. Similar to other minerals, the silicon refining industry has demonstrated the capacity to adapt to the rapid growth in demand, albeit at the expense of increasing concentration and significant price volatility. The supply was initially affected by a glut that began in 2015, followed by a period of supply tightness in 2021. Currently, there is an oversupply situation, with a high volume of capacities developed in China in line with its downstream solar PV capacities. Silicon prices fell by 74% in 2023 to around USD 8 per kilogramme.

China's share of solar-grade silicon grew from 27% in 2010 to over 80% today. The current price context and local energy prices are adding pressure on European solar-grade polysilicon manufacturers, with some capacities closing down. US restrictions on solar PV imports related to concerns of forced labour have increased demand for supplies outside of China, with some plants being developed in the United States recently.

Recycling silicon remains challenging due to weak economic incentives, driven by the low cost of the material input and the prevailing low-price environment affecting the 6N refined silicon market. Historically, solar PV recycling players have prioritised base materials present in larger volumes (such as copper, aluminium and glass), or precious metals such as silver, rather than silicon. However, some European are developing plants designed to recycle silicon.

Phosphoric acid

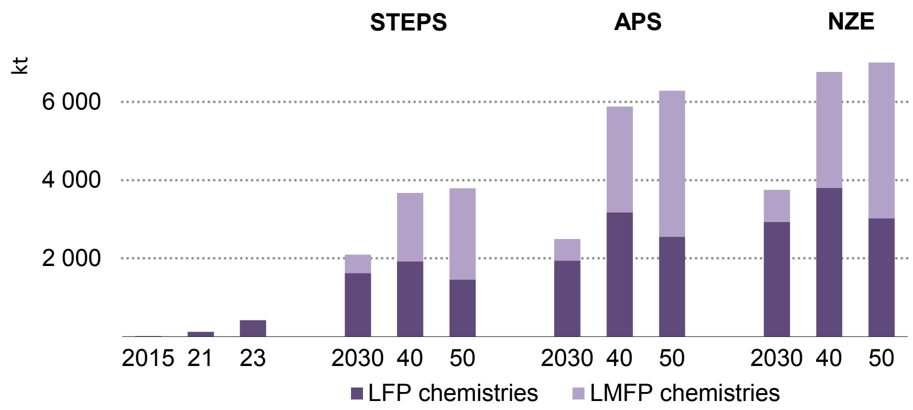
The success of LFP battery chemistries is creating a market for a new input, iron phosphate, and its precursor – purified phosphoric acid. As LFP cathode production rises, so does demand for this high-purity input, reaching over 2 Mt in the APS by 2030 and close to 4 Mt in the NZE Scenario. Further demand growth for high phosphoric acid comes from next-generation lithium-iron phosphate manganese (LMFP) chemistries, whose higher performance is likely to further popularise EV batteries containing phosphate. In 2040, demand rises to almost 6 Mt in the APS and over 6.5 Mt in the NZE Scenario.

Phosphates are cheaper than the metals they replace from previous battery compositions (cobalt, nickel) and are currently produced in vast quantities for fertiliser applications. About 220 Mt of phososphate rocks are extracted each year, containing about 28 Mt of phosphorus, and enough to produce over 80 Mt of phosphoric acid.

Three challenges could arise from these developments:

- Increased competition with agricultural supply – despite demand in smaller volumes and higher-grade requirements, additional demand from the energy sector could change supply and demand balances in the fertiliser market.
- Geological deposits for phosphate rocks are sufficient, but questions remain regarding mining capacities, particularly the best deposits for the production of purified phosphoric acid. This process requires high grade and low rates of heavy metals such as cadmium. Some LFP supply chain investments are oriented towards countries with significant phosphate resources, such as Morocco, which also benefits from a number of favourable free trade agreements.
- An ability for new players to access supplies already secured by refining. Once concentrated in China, LFP technologies have gained popularity elsewhere including among North American gigafactories. These new players need to find a channel to source materials reliably.

Phosphoric acid demand from the EV sector by scenario



Platinum group metals

Prices for platinum group metals (PGMs) remained under pressure for the past year, driven in large part by poor automotive sales. The basket price, defined as the average price of the five PGMs (platinum, palladium, rhodium, iridium and ruthenium) weighted by production, seems unlikely to increase meaningfully in the short term. Although the five PGMs occur together in nature, divergent market outlooks are complicating strategic decision-making for these elements.

In the near term, prices for platinum, iridium and ruthenium are expected to remain stable, with platinum having modest upside potential. Rhodium and palladium are likely to remain under pressure due to lower demand for internal combustion engine (ICE) emissions catalysts, which represents about 90% of demand for rhodium and 80% of demand for palladium. Future increases in platinum demand remain subject to the future of hydrogen fuel cell vehicle sales, along with demand from existing industrial and ICE applications.

Palladium and rhodium demand are likely to decline structurally due to the uptake of EVs. In addition, growing secondary supplies are likely to exert further pressure on producers, especially for North American mines mining palladium-rich ores.

Demand for iridium and ruthenium are likely to increase consistently in the coming years thanks to demand for membrane electrodes, including those used in proton exchange membrane hydrogen electrolysers. This is likely in spite of continued technical research and development to reduce the amount of precious metals per unit product. Price volatility in the iridium market is expected to continue, driven by concerns over long-term supply. However, given the relatively small contribution of iridium and ruthenium to the PGM basket, prices for these metals will have to increase significantly to motivate structural increases in supply.

On the supply side, near-term shocks remain possible thanks to persistent electricity system issues in South Africa and geopolitical concerns impacting Russian palladium supplies from Norilsk. Since the second half of 2023, South African PGM miners including Sibanye-Stillwater, Anglo-American Platinum and Impala Platinum have announced cost-cutting measures to mitigate the impact of low prices. These measures, which include project deferrals and shutting shafts, have not meaningfully boosted prices, which have remained anaemic. If the current price environment continues, further closures might occur, jeopardising long-term primary supply for all five metals.

3. Clean energy transition risk assessments

IEA's mineral-specific "clean energy transition risk assessment" framework

Supply risks	Expected pace of demand growth
	Short-term supply-demand balances
	Long-term market balances in climate-driven scenarios
	Observed price volatility
	Impacts on clean energy cost
Geopolitical risks	Geographical concentration of mined supply
	Geographical concentration of refined supply
	N-1 demand and supply balances
	Export risks of major suppliers
	Hurdles to develop new projects in diversified regions
Barriers to respond to disruption	Visible stock levels
	Transparency of pricing schemes
	Availability of options to moderate demand
	Status of secondary supply
Exposure to ESG and climate risks	Environmental performance: mining
	Environmental performance: refining
	Social and governance performance
	Exposure to natural hazards and climate risks - water stress
	Exposure to natural hazards and climate risks - earthquake

Notes: ESG = environmental, social and governance. "N-1" refers to the case that excludes anticipated supply from the largest supplier and projected demand from that country from global market balances.

Mineral-specific “clean energy transition risk assessment” framework

Understanding potential risks across the critical mineral supply chain is an essential step to enhance readiness against potential disruptions and devise necessary policy actions. An approach to mineral security may vary depending on each mineral’s market context and risk exposure. Conducting structured risk assessments can assist policymakers in identifying vulnerabilities in the supply chain, devising appropriate security measures, and directing policy efforts to where they are most needed.

We have performed “Clean energy transition risk assessments” for the six key energy transition minerals: copper, lithium, nickel, cobalt, graphite, and rare earth elements. These assessments are based on a comprehensive framework that combines both quantitative and qualitative analyses, to understand potential risk areas that could hamper progress towards energy transitions. The framework encompasses four main categories: supply risks, geopolitical risks, barriers to respond to disruptions, and exposure to environmental, social, and governance (ESG) and climate risks (see Annex for detailed evaluation criteria).

The first category (**supply risks**) assesses five dimensions.

- **Pace of demand growth** compares projected annual average demand growth rates in the Announced Pledges Scenario (APS) between 2023 and 2030 in relation to historical growth rates between 2010 and 2019.
- **Short-term market balances** assesses the near-term balances between expected supply and primary supply requirements.
- **Long-term market balances in climate-driven scenarios** reviews the balances between expected supply and primary supply requirements in 2040 in the APS.
- **Observed price volatility** evaluates historical price volatility based on monthly prices between 2011 and 2023.
- **Impact on clean energy cost** examines the share of a material in the total cost of end-use clean energy technologies to assess how price volatility could affect clean energy deployment.

The second category (**geopolitical risks**) assesses five dimensions.

- **Geographical concentration of mined supply** assesses the expected share of the top three producing countries for mining in 2030 under the base case supply scenario.
- **Geographical concentration of refined supply** assesses the expected share of the top three producing countries for refining in 2030 under the base case supply scenario.

- **N-1 supply and demand balances** reviews market balances excluding the largest supplier by comparing the N-1 supply and material requirements in 2030 in the APS (refined product basis).
- **Export risks of major suppliers** assesses the risks of trade restriction measures by examining the weighted average export restriction risk score of the current production portfolio for both mining and refining, based on the Organisation for Economic Co-operation and Development's (OECD's) inventory of export restrictions on industrial raw materials and announced intentions.
- **Hurdles to develop new projects in diversified regions** conducts qualitative assessments of challenges in building supply chains in geographically diverse regions, such as lead time, capital requirements and technological barriers.

The third category (**barriers to respond to disruptions**) assesses four dimensions.

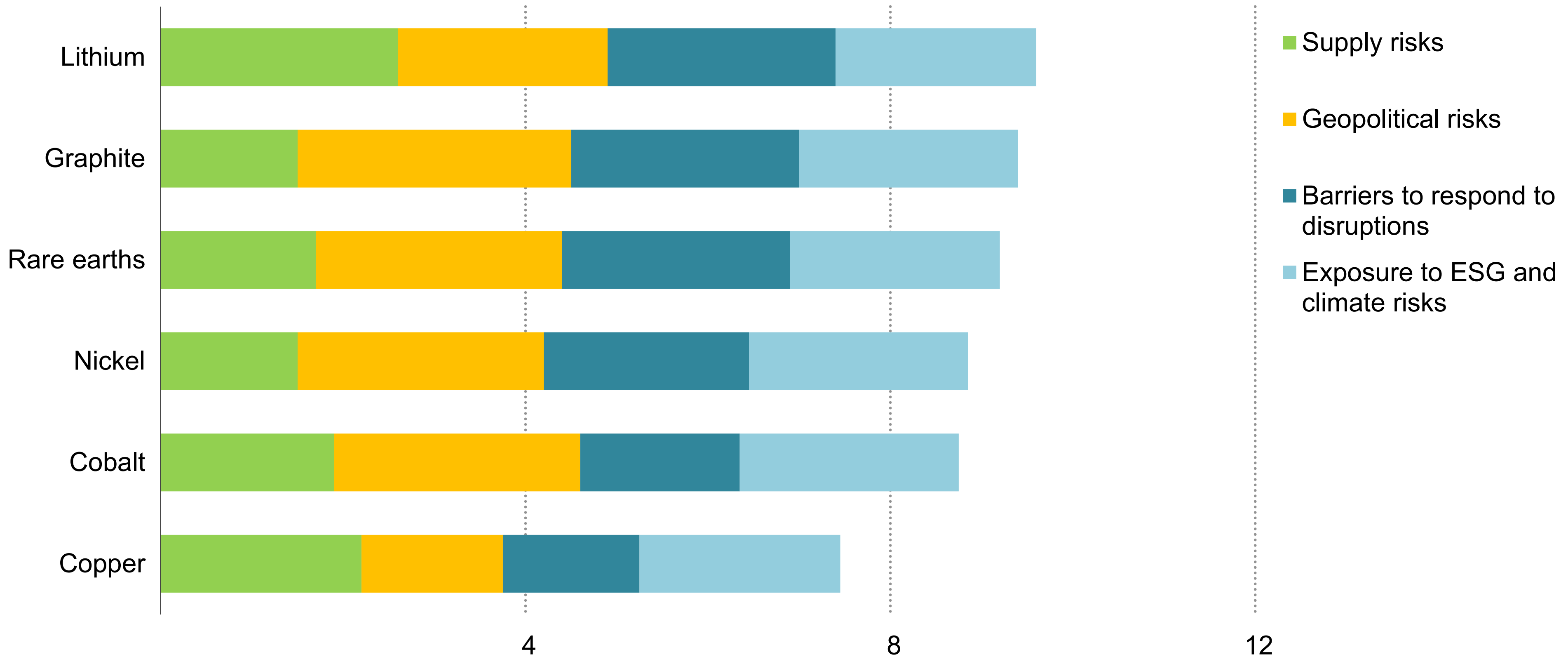
- **Visible stock levels** reviews stock levels at major exchanges. While exchange stocks represent only a fraction of the industry's overall stock levels, they offer a valuable indication of an accessible buffer during disruptions.
- **Transparency of pricing schemes** conducts a qualitative assessment of market liquidity, transparency of pricing schemes and the availability of financial tools to hedge price risks.
- **Availability of options to moderate demand** assesses possible demand-side and technology-switching options to moderate demand growth in the event of supply tightness.
- **Status of secondary supply** assesses the ability of secondary supply to ramp up during market tightness by examining the share of secondary supply in total supply and its potential for growth.

The fourth category (**exposure to ESG and climate risks**) assesses five dimensions.

- **Environmental performance of mining** reviews the weighted average enviromental performance score of today's mined production, based on selected indicators in Yale's Environmental Performance Index.
- **Environmental performance of refining** reviews the weighted average grid carbon intensity of the regions refining minerals today, considering that refining operations are highly electricity-intensive.
- **Social and governance performance** assesses the weighted average corruption, human rights and conflict score of today's mined production, based on relevant indicators in the V-Dem database.
- **Exposure to water stress** assesses the share of mine production located in areas with high and extreme high-water stress and arid conditions.
- **Exposure to earthquake risks** assesses the share of mine production located in areas with high earthquake risks.

Overall: Lithium and graphite show the highest risk scores, though the specific areas of exposure vary by mineral

Aggregate risk score by mineral



Copper: Assessment results

Area	Score	Rationale
Supply risks	**Medium**	
Pace of demand growth	Low	Projected pace of demand growth is in line with historical growth rates
Short-term market balances	Medium	Supply could meet near-term demand, but risks of tightness if disruption occurs beyond usual range
Long-term market balances	High	Expected base case supply falls significantly short of the primary supply requirements in 2040
Observed price volatility	Low	Historical price movement has been less volatile compared with other commodities
Impact on clean energy cost	High	Price spikes could significantly affect grid deployment (20% of capital costs). Copper in lithium-ion anode current collector is difficult to be replaced, thus price spikes can have major impacts on battery prices
Geopolitical risks	**Low**	
Geographical concentration: mining	Low	Expected top 3 share in 2030 is around 48% and top 1 share is around 23%
Geographical concentration: refining	Low	Expected top 3 share in 2030 is around 60% and top 1 country accounts for less than half of global supply
N-1 supply and demand balances	Low	N-1 supply in 2030 able to serve N-1 demand
Export risks of major suppliers	Medium	Risk score 2.7 (mining 2.2/refining 3.3)
Hurdles for diversification	High	Challenges of declining ore quality, very low global average grade (0.6%), few major resources of high quality to exploit. Capital and operating costs increasing, coupled with long lead times to build new mines
Barrier to respond to disruption	**Low**	
Visible stock levels	Medium	Able to monitor stock levels at major exchanges, but the current exchange stocks at low levels
Transparency of pricing schemes	Low	Established regulated market trading with ample liquidity
Availability of options to moderate demand	Medium	Scope to moderate demand through scaling up recycling and scrap use and substitution for aluminium. However, copper is irreplaceable for many applications (e.g. lithium-ion anode current collectors, subsea cables). The replacement of underground power lines with aluminium requires additional cost
Status of secondary supply	Low	Sizeable secondary supply and growing direct use of scrap, which could be tapped in times of price spikes
Exposure to ESG & climate risk	**Medium**	
Environmental performance: mining	Medium	Weighted average score 47
Environmental performance: refining	High	467 g CO_2/kWh
Social and governance performance	Low	Weighted average score 0.68
Exposure to water stress	High	52% of mine production located in high-risk areas
Exposure to earthquake risks	Medium	46% of mine production located in high-risk areas

Lithium: Assessment results

Area	Score	Rationale
Supply risks	**High**	
Pace of demand growth	High	Projected pace of demand growth is materially higher than the rates observed in the last decade
Short-term market balances	Low	Sufficient supply expected to serve short-term demand
Long-term market balances	High	Expected base case supply meets less than 40% of the primary supply requirements in 2040
Observed price volatility	High	High volatile price movements observed in recent years
Impact on clean energy cost	High	20% of battery pack cost. Fluctuation of prices has major impacts on battery prices and deployment
Geopolitical risks	**Medium**	
Geographical concentration: mining	Medium	Expected top 3 share in 2030 is around 68% and top 1 share is around 33%
Geographical concentration: refining	High	Expected top 3 share in 2030 is above 80% and top 1 country accounts for more than half of global supply
N-1 supply and demand balances	Medium	Expected ex-China supply could serve around half of APS ex-China material requirements in 2030
Export risks of major suppliers	Medium	Risk score 3.1 (mining 2.4/refining 3.8)
Hurdles for diversification	Medium	New capacities do not necessarily involve higher capital, but need to overcome technological barriers
Barrier to respond to disruption	**High**	
Visible stock levels	Medium	Limited information about visible stock levels, but accumulated industry stocks are expected
Transparency of pricing schemes	Medium	Early-stage regulated market trading, but liquidity is still lacking
Availability of options to moderate demand	High	Limited options to reduce demand. Sodium-ion may ease concerns, but has limitations to be adopted in major transport segments
Status of secondary supply	High	Limited share of secondary supply as of today, but set to increase in future years
Exposure to ESG & climate risk	**Medium**	
Environmental performance: mining	Medium	Weighted average score 59
Environmental performance: refining	High	531 g CO_2/kWh
Social and governance performance	Low	Weighted average score 0.78
Exposure to water stress	High	50% of mine production located in high-risk areas
Exposure to earthquake risks	Medium	26% of mine production located in high-risk areas

Nickel: Assessment results

Area	Score	Rationale
Supply risks	**Low**	
Pace of demand growth	Low	Projected demand growth rates are in line with historical growth rates
Short-term market balances	Low	Sufficient supply expected to serve short-term demand
Long-term market balances	Medium	Expected base case mine supply meets a large portion of the primary supply requirements in 2040 due to the rise of Indonesian output, but lack of sufficient nickel sulphate capacity remains an issue
Observed price volatility	Low	Historical price movement has been less volatile compared with other commodities
Impact on clean energy cost	Medium	6% of battery pack cost in 2023. Fluctuation of nickel prices can have major impacts on battery prices
Geopolitical risks	**High**	
Geographical concentration: mining	High	Expected top 3 share in 2030 is around 75% and top 1 share is around 61%
Geographical concentration: refining	High	Expected top 3 share in 2030 is around 67% and top 1 country supplies more than half of global output
N-1 supply and demand balances	Medium	N-1 supply serves 35% of N-1 requirements in 2030 in the APS
Export risks of major suppliers	Medium	Risk score 3.9 (mining 3.8/refining 4.1)
Hurdles for diversification	High	Most diversified projects in the pipeline in the base case or high production case are located in higher-cost jurisdictions, posing significant barriers to entry without mechanisms to incentivise high ESG performance
Barrier to respond to disruption	**Medium**	
Visible stock levels	Medium	Nickel exchange stocks at historically low levels
Transparency of pricing schemes	Medium	Established regulated market trading but liquidity has been reduced considerably in recent years
Availability of options to moderate demand	Medium	Possible to shift more towards lithium iron phosphate (LFP) or lithium manganese iron phosphate (LMFP) at the expense of long-rage electric vehicles
Status of secondary supply	High	Limited share of secondary supply as of today, but set to increase in future years
Exposure to ESG & climate risk	**High**	
Environmental performance: mining	High	Weighted average score 35.5
Environmental performance: refining	High	603 g CO_2/kWh, one of the highest
Social and governance performance	Medium	Weighted average score 0.65
Exposure to water stress	Low	12% of mine production located in high-risk areas
Exposure to earthquake risks	Low	19% of mine production located in high-risk areas (Weda Bay / South Sulawesi assessed as low risk)

Cobalt: Assessment results

Area	Score	Rationale
Supply risks	**Medium**	
Pace of demand growth	Low	Projected demand growth rates are in line with historical growth rates
Short-term market balances	Low	Sufficient supply expected to serve short-term demand
Long-term market balances	Medium	Expected base case mine supply meets 70% of the primary supply requirements in 2040
Observed price volatility	High	Highly volatile price movements observed in the past decade
Impact on clean energy cost	Medium	2% of battery pack cost in 2023 with low cobalt prices, but the share was 5-6% in the past, which means cobalt would have modest impacts on battery cost and deployment
Geopolitical risks	**High**	
Geographical concentration: mining	High	Expected top 3 share in 2030 is around 84% and top 1 share is around 66%
Geographical concentration: refining	High	Expected top 3 share in 2030 is around 84% and top 1 country supplies three-quarters of global output
N-1 supply and demand balances	Medium	N-1 supply serves 37% of N-1 requirements in 2030 in the APS
Export risks of major suppliers	Medium	Risk score 3.3 (mining 2.4/refining 4.1)
Hurdles for diversification	High	The low-price environment and relatively downbeat demand outlook present challenges in building diversified assets whereas projects continue to be developed in the Democratic Republic of the Congo, Indonesia and the People's Republic of China (hereafter "China")
Barrier to respond to disruption	**Medium**	
Visible stock levels	Medium	Minimal amount of exchange stocks
Transparency of pricing schemes	Medium	Early stage regulated market trading but liquidity is still lacking
Availability of options to moderate demand	Low	Ongoing efforts to reduce cobalt use in cathode chemistries (e.g. LFP, LMFP)
Status of secondary supply	Medium	Around 10% of secondary supply share, but set to improve in future years
Exposure to ESG & climate risk	**High**	
Environmental performance: mining	High	Weighted average score 36
Environmental performance: refining	High	533 g CO_2/kWh
Social and governance performance	Medium	Weighted average score 0.47
Exposure to water stress	Low	5% of mine production located in high-risk areas
Exposure to earthquake risks	Low	4% of mine production located in high-risk areas

Graphite: Assessment results

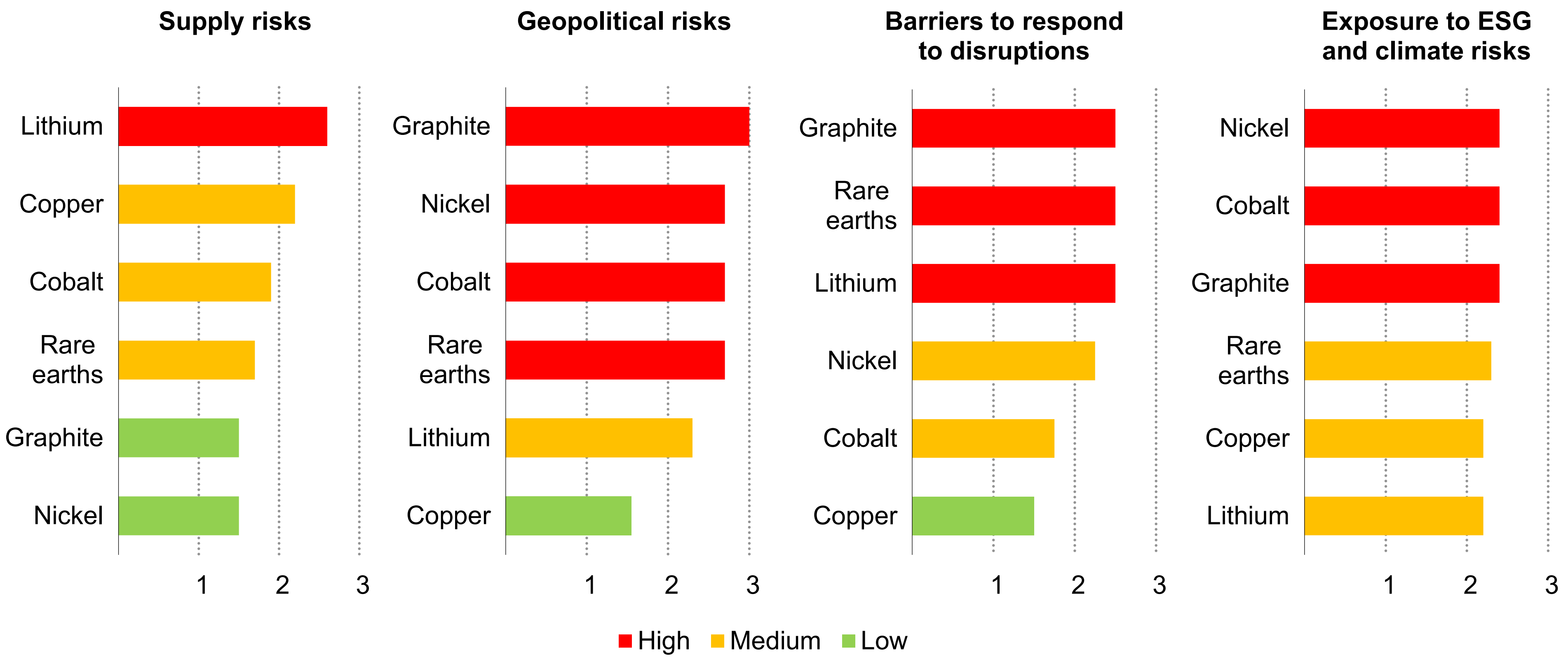
Area	Score	Rationale
Supply risks	**Low**	
Pace of demand growth	High	Projected pace of future demand growth is significantly higher than the rate observed in the 2010s
Short-term market balances	Low	Sufficient supply expected to serve short-term demand
Long-term market balances	Medium	Expected base case mine supply meets two-thirds of the primary supply requirements in 2040, although synthetic graphite could fill the gap (at cost)
Observed price volatility	Low	Historical price movement has been less volatile compared with other commodities
Impact on clean energy cost	Low	Graphite is not a major part of total battery pack costs
Geopolitical risks	**High**	
Geographical concentration: mining	High	Expected top 3 share in 2030 is around 88% and top 1 share is around 69%
Geographical concentration: refining	High	Battery-grade supply continues to be dominated by China, with 93% share (down from 100% today)
N-1 supply and demand balances	High	Very limited supply potential to serve N-1 battery-grade graphite requirements in 2030
Export risks of major suppliers	High	Risk score 4.4 (mining 4.5/refining 4.4)
Hurdles for diversification	High	New projects are capital-intensive, requiring up to two times higher capital requirements than Chinese projects. New graphite project developers have limited financial capacity
Barrier to respond to disruption	**High**	
Visible stock levels	Medium	Limited information about visible stock levels, but accumulated industry stocks are estimated to exist
Transparency of pricing schemes	High	Price reporting driven through survey pricing and unregulated platforms with limited liquidity
Availability of options to moderate demand	Medium	Silicon could take growing shares in anodes, but unlikely to challenge graphite use in the near term
Status of secondary supply	High	Share of secondary supply remains low, with limited ability to scale up secondary supply quickly
Exposure to ESG & climate risk	**High**	
Environmental performance: mining	Medium	Weighted average score 41
Environmental performance: refining	High	577 g CO_2/kWh
Social and governance performance	High	Weighted average score 0.3
Exposure to water stress	Medium	Many natural graphite mines in Heilongjiang and Inner Mongolia, regions with medium water stress
Exposure to earthquake risks	Low	Heilongjiang and Inner Mongolia are not exposed to major earthquake risks

Rare earth elements: Assessment results

Area	Score	Rationale
Supply risks	**Medium**	
Pace of demand growth	Low	Expected demand growth rates are in line with historical growth rates
Short-term market balances	Low	Sufficient supply expected to serve short-term demand
Long-term market balances	Medium	Expected base case mine supply meets 70% of the primary supply requirements in 2040
Observed price volatility	High	Highly volatile price movements observed in recent years
Impact on clean energy cost	Low	While crucial for performance, rare earth elements are not a major contributor to final clean energy cost
Geopolitical risks	**High**	
Geographical concentration: mining	High	Expected top 3 share in 2030 is over 80% and top 1 share is around 55%
Geographical concentration: refining	High	Expected magnet rare earth supply continues to be dominated by China, with 77% share
N-1 supply and demand balances	Low	N-1 supply could serve N-1 requirements in 2030 in the APS
Export risks of major suppliers	High	Risk score 4.5 (mining 4.1/refining 4.8)
Hurdles for diversification	High	High entry barrier due to extensive resource endowment, accumulated technological know-how in the top producing country. Disadvantaged in terms of scale and costs (energy costs and cross-border trade taxes)
Barrier to respond to disruption	**High**	
Visible stock levels	High	Limited information about visible stock levels
Transparency of pricing schemes	High	Price reporting driven through survey pricing and unregulated platforms with limited liquidity
Availability of options to moderate demand	Medium	Alternative new technologies have lower magnetic density and coercivity, and may struggle to compete commercially with the rare earth-based alternatives that produce the strongest known permanent magnets
Status of secondary supply	Medium	Share of secondary supply remains modest but hard to tap in times of price spikes
Exposure to ESG & climate risk	**Medium**	
Environmental performance: mining	Medium	Weighted average score 40.2
Environmental performance: refining	High	607 g CO_2/kWh, one of the highest
Social and governance performance	Medium	Weighted average score 0.34
Exposure to water stress	Medium	Infrastructure located in Australia and Inner Mongolia (China) are in regions at high risk of water stress
Exposure to earthquake risks	Medium	Infrastructure located in Inner Mongolia (China), United States, India and Japan are in regions of medium to high risk of seismic activity

Risk score by category: Lithium and copper are more exposed to supply and volume risks whereas graphite, cobalt, rare earths and nickel face more substantial geopolitical risks

Risk score by category and mineral



Note: High = score above 2.33, Medium = score between 2.33 and 1.67, Low = score less than 1.67.

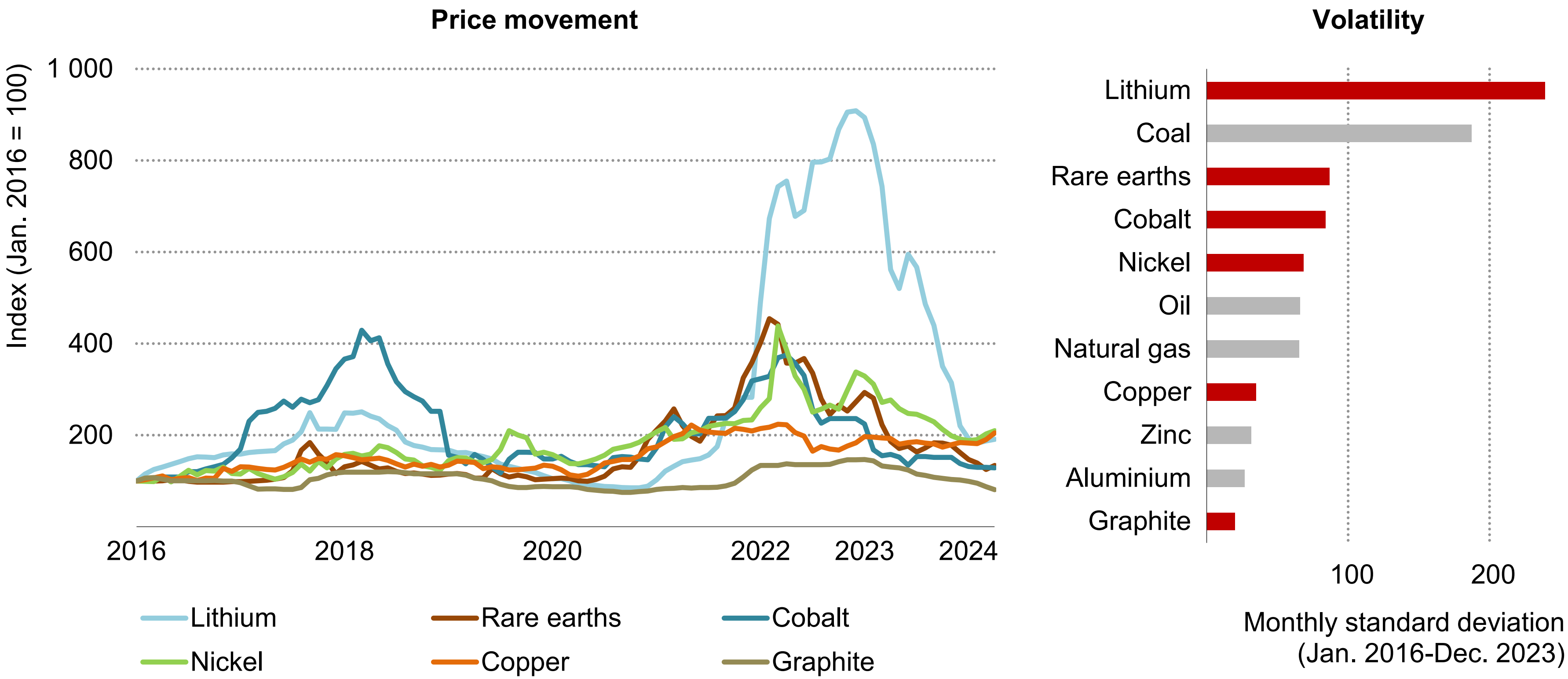
Supply risks: Lithium and copper are most exposed to supply risks

Risk score for supply risks – aggregate and individual dimensions

Material	Overall score	Pace of demand growth	Short-term market balance	Long-term market balance	Observed price volatility	Impact on clean energy cost
Lithium	High (2.6)	High	Low	High	High	High
Copper	Medium (2.2)	Low	Medium	High	Low	High
Cobalt	Medium (1.9)	Low	Low	Medium	High	Medium
Rare earth elements	Medium (1.7)	Low	Low	Medium	High	Low
Graphite	Low (1.5)	High	Low	Medium	Low	Low
Nickel	Low (1.5)	Low	Low	Medium	Low	Medium

Supply risks: Prices for critical minerals tend to be volatile, often more so than for fossil fuels and base metals

Price movement and volatility of selected commodities



Notes: Assessment based on the London Metal Exchange (LME) Lithium Carbonate Global Average, LME Nickel Cash, LME Cobalt Cash, LME Copper Grade A Cash prices, China flake graphite (-194 free on board) and neodymium oxide 99.5-99.9% Min China. Nominal prices.

Sources: IEA analysis based on S&P Global and Bloomberg.

Geopolitical risks: Most minerals are highly exposed to geopolitical risks

Risk score for geopolitical risks – aggregate and individual dimensions

Material	Overall score	Geographical concentration of mining	Geographical concentration of refining	N-1 supply and demand balances	Export risks of major suppliers	Hurdles for diversification
Graphite	**High (3.0)**	High	High	High	High	High
Nickel	**High (2.7)**	High	High	Medium	Medium	High
Cobalt	**High (2.7)**	High	High	Medium	Medium	High
Rare earth elements	**High (2.7)**	High	High	Low	High	High
Lithium	**Medium (2.3)**	Medium	High	Medium	Medium	Medium
Copper	**Low (1.6)**	Low	Low	Low	Medium	High

Barriers to respond to disruptions: Graphite, rare earth elements and lithium have relatively little ability to respond to potential supply disruptions

Risk score for ability to respond to disruptions – aggregate and individual dimensions

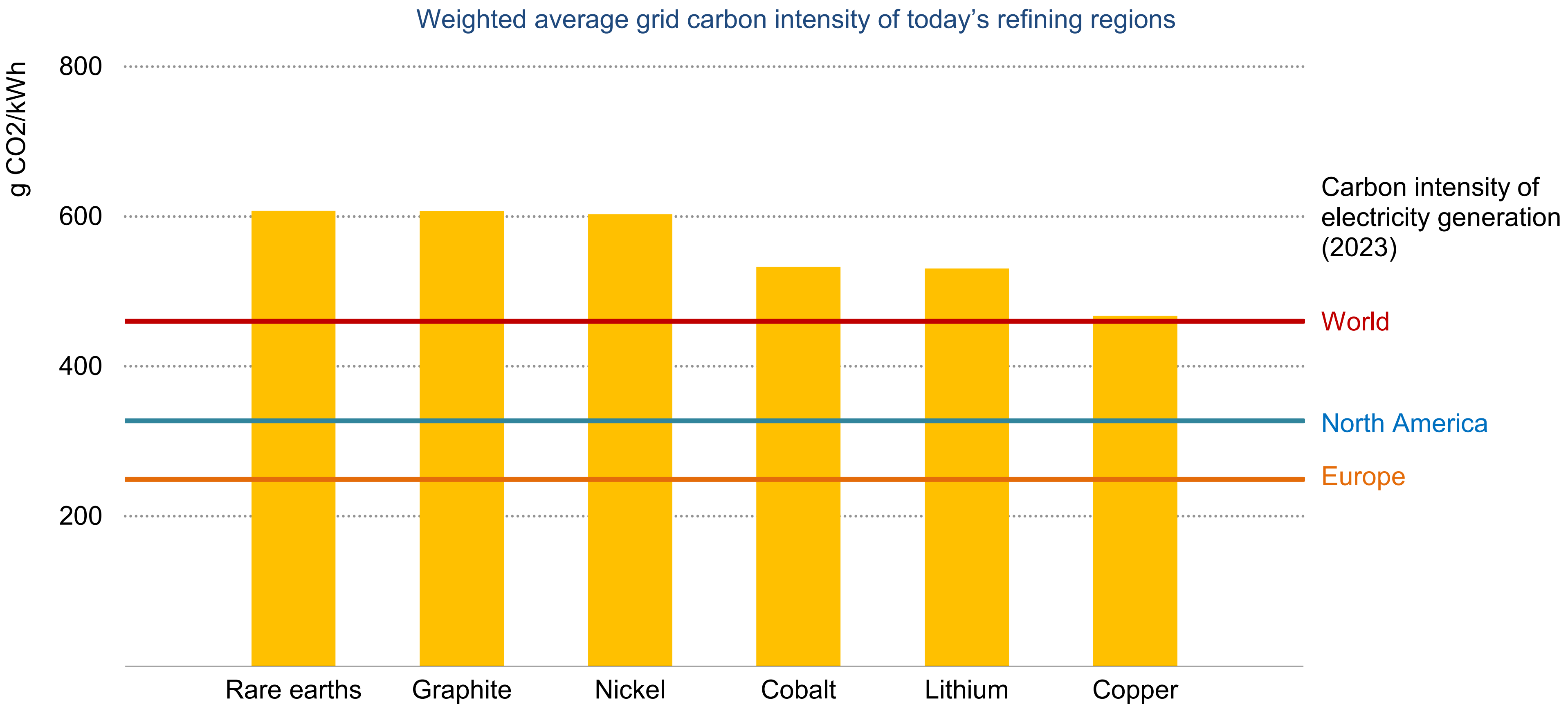
Material	Overall score	Visible stock levels	Transparency of pricing schemes	Availability of options to moderate demand	Status of secondary supply
Graphite	High (2.5)	Medium	High	Medium	High
Rare earth elements	High (2.5)	High	High	Medium	Medium
Lithium	High (2.5)	Medium	Medium	High	High
Nickel	Medium (2.3)	Medium	Medium	Medium	High
Cobalt	Medium (1.8)	Medium	Medium	Low	Medium
Copper	Low (1.5)	Medium	Low	Medium	Low

Exposure to ESG and climate risks: Most minerals are exposed to high environmental risks

Risk score for exposure to ESG and climate risks – aggregate and individual dimensions

Material	Overall score	Environmental performance - Mining	Environmental performance - Refining	Social and governance performance	Exposure to water stress	Exposure to earthquake risks
Graphite	High (2.4)	Medium	High	High	Medium	Low
Nickel	High (2.4)	High	High	Medium	Low	Low
Cobalt	High (2.4)	High	High	Medium	Low	Low
Rare earth elements	Medium (2.3)	Medium	High	Medium	Medium	Medium
Lithium	Medium (2.2)	Medium	High	Low	High	Medium
Copper	Medium (2.2)	Medium	High	Low	High	Medium

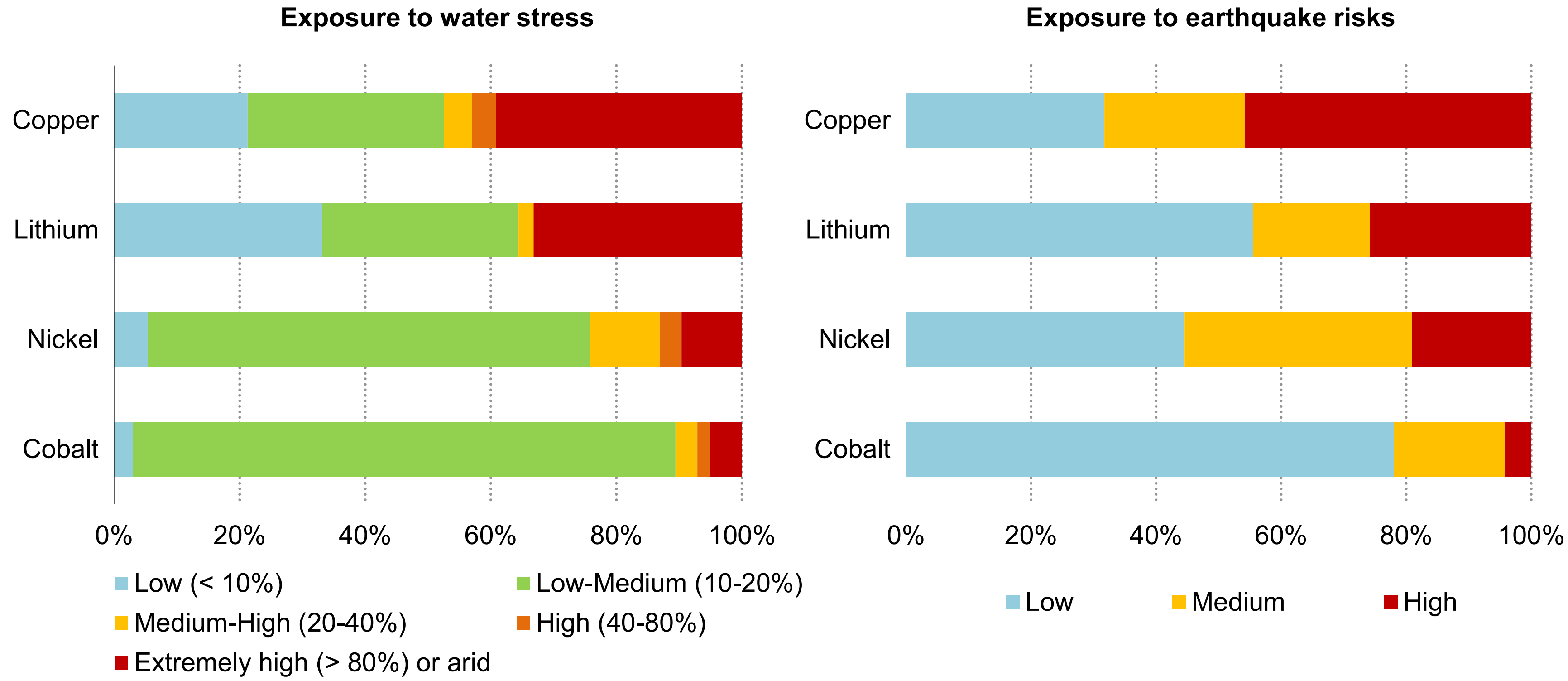
Exposure to ESG and climate risks: Today's refining operations occur in places with higher carbon intensity of the grid, mostly in regions relying on coal-based electricity



Notes: The carbon intensity for natural gas-based power generation is around 427 gCO_2/kWh. For all minerals, the weighted average carbon intensity of the grid is higher than this, hinting that operations take place in regions relying on coal-based electricity. In some places (e.g. Indonesia), the rise of refining operations is being served mainly by off-grid, which runs entirely based on coal.

Exposure to ESG and climate risks: Mining assets are exposed to growing water stress and earthquake risks

Share of production volume by water stress and earthquake risk levels for selected minerals, 2023

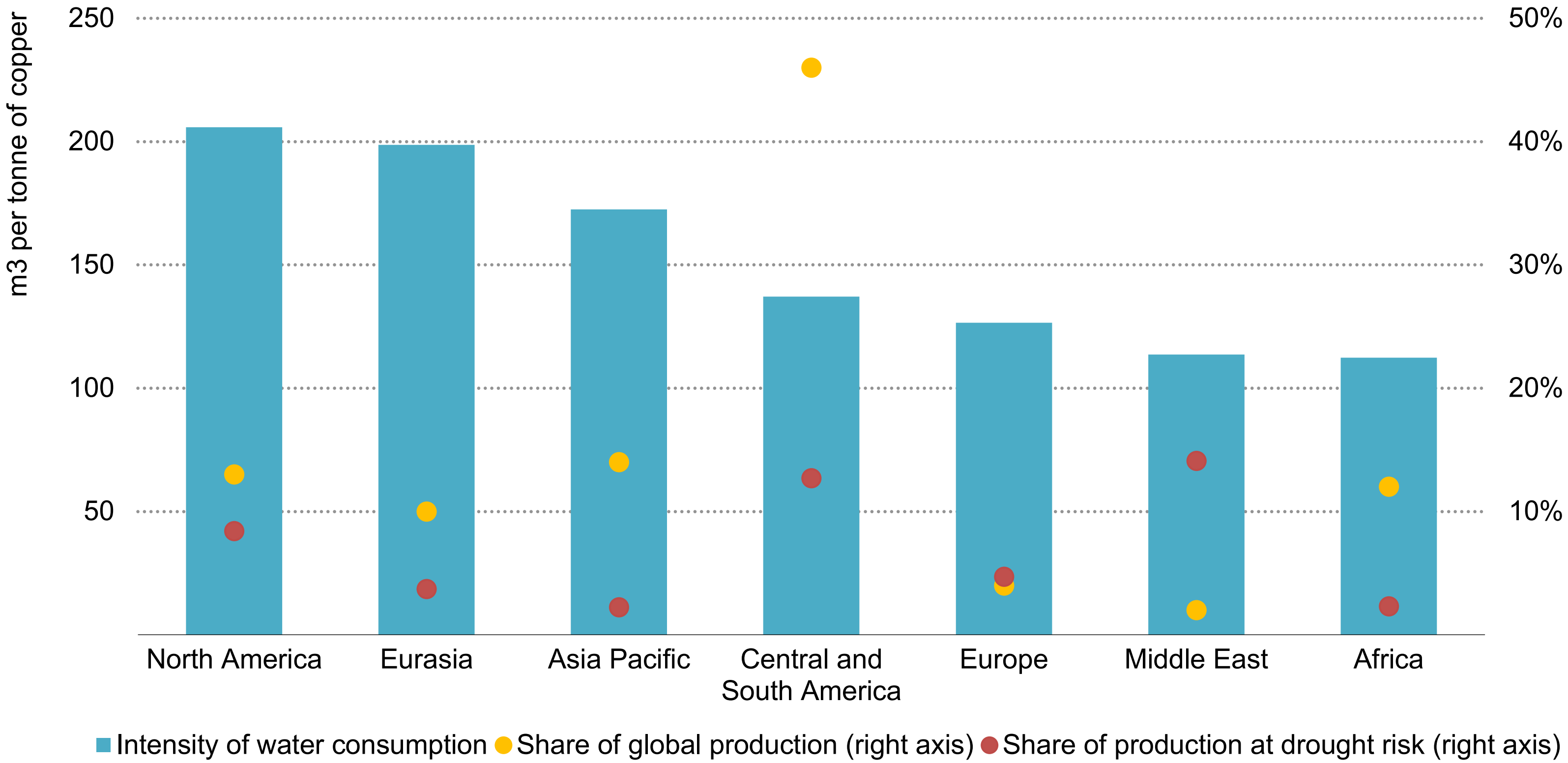


Note: Water stress levels are as defined in the Aqueduct 3.0 dataset according to the ratio of total water withdrawals over the total available surface and groundwater supplies. Earthquake risk levels are as defined in the GEM Global Seismic Hazard Map (v2023.1) based on peak ground acceleration (PGA) with a 10% probability of being exceeded in 50 years.

Sources: IEA analysis based on S&P Global, WRI (2019), Aqueduct 3.0, and GEM (2023), Global Seismic Hazard Map.

Around 10% of global copper production faces supply risks related to droughts

Water consumption intensity and drought risk in copper production by region, 2022



Notes: Production at risk is the exposure percentage of the production at risk due to drought. It reflects the interaction of how water is used on site in the context of identified external climate risks, the operations water source matrix, its water efficiency and operational resilience. Drought risks are based on statistical analysis of monthly precipitation data and trends.

Source: Data provided by Skarn Associates.

4. Implications

Four focus areas for policy makers, industry, and consumers to promote reliable and sustainable supplies of critical minerals

The picture that emerges from the analysis in previous chapters is a complex one. It shows some commonalities across the critical minerals examined, notably in the combination of rising demand and high concentrations among suppliers. However, it also highlights the specificities of the outlook in each case, with different sources of strain and opportunities for growth and for substitution.

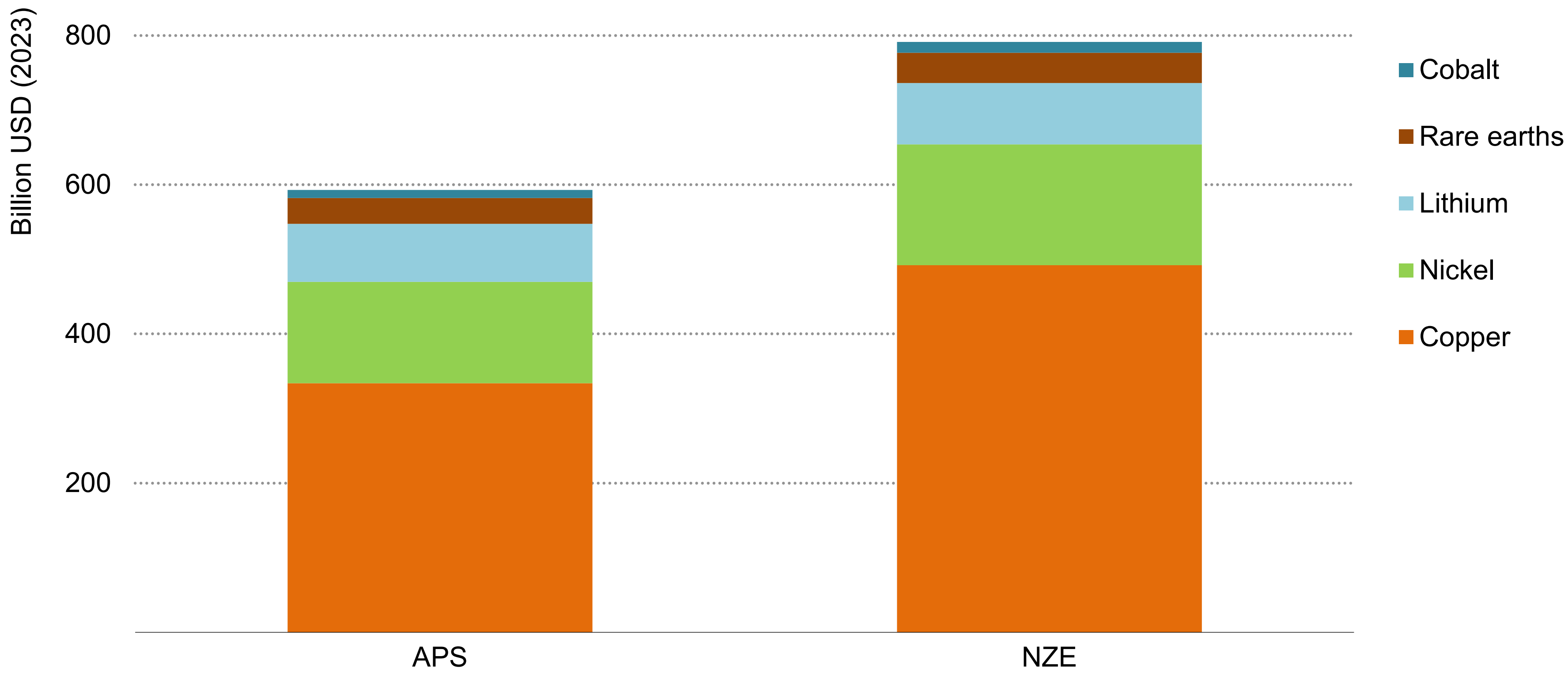
This final chapter reflects on four broad themes that apply, to a greater or lesser extent, to all of the minerals examined. These areas constitute an agenda for future work by policy makers and industry as they seek to ensure reliable and sustainable supplies of critical minerals:

- **Investment in diversified supply.** Long-term security of supply is typically a question of adequate investment, but in the case of critical minerals it is not only the adequacy of supply that matters but also the diversity. It can be very challenging for new entrants to gain a foothold in markets with well-established incumbents. This section looks at the financing options open to governments that are seeking to encourage or de-risk investments in diversified sources of supply.
- **Recycling, innovation, and behavioural change.** Strategies for critical minerals security sometimes have an imbalanced focus on expanding supply, but measures to temper demand are essential. Recycling creates a valuable secondary source of minerals that relieves the pressure on primary supply; technology innovations have proven potential to ease strains on the supply side; and behavioural issues and consumer preferences can have strong implications for vehicle and battery sizes, and therefore on mineral requirements.
- **Market transparency.** Transparency of pricing and market information brings important benefits to all aspects of the supply chain, but for the moment these aspects remain weak for many critical minerals. This section considers options to improve the quality of information available to market participants, including moves towards market-based price discovery.
- **Sustainable and responsible supplies.** As production of critical minerals expands, it will be crucial to ensure that projects do not come at the expense of the people involved or result in local environmental damage. This section discusses how the benefits associated with mineral production, such as revenue and jobs, can be felt by producer countries and communities.

Investment in diversified supply

Major capital investment is required across all minerals to meet demand in climate-driven scenarios

Capital requirements for mining to meet 2040 demand in the APS and NZE Scenario



Notes: Capital requirements for the APS and NZE Scenario are calculated based on compiled capital intensity by region and production route. The values also assume an increased average capital intensity over today due to declining ore grades.
Source: IEA analysis based on data from S&P Global and company reports.

The NZE Scenario requires around USD 800 billion of investment in mining between today and 2040

Capital requirements to meet climate goals

Large amounts of investment will be required to develop new supply sources to meet the required demand for critical minerals in climate-driven scenarios. For mining, we estimate that approximately USD 590 billion is required in new capital investments between now and 2040 in the Announced Pledges Scenario (APS). As the Net Zero Emissions by 2050 (NZE) Scenario sees faster deployment of clean energy technologies, total capital requirements are about 30% higher at USD 790 billion over the same period (excluding sustaining capital expenditure).

The largest investment among the critical minerals is in copper. Capital requirements to 2040 for copper mining are USD 330 billion in the APS and USD 490 billion in the NZE Scenario. These amounts reflect not only the significant levels of demand, but also escalating capital requirements per tonne of ore caused by declining ore quality. Although all minerals face this challenge, it is more acute in mature and established markets such as copper. Nickel sees the second-largest levels of capital spending (USD 160 billion to 2040 in the NZE Scenario), followed by lithium (USD 80 billion). Lower but still significant amounts of investment are also needed for new refining and smelting facilities. Part of these increases in capital investment need to be made in a way that fosters a more diversified array of supply sources in the future.

Key financing challenges

Financing diversified critical mineral supply chains faces numerous challenges, primarily stemming from two underlying factors: high input costs and long-term price uncertainty.

Supply-side cost inflation, driven by rising energy prices and declining resource quality over the past few years, have persisted even as commodity prices have dropped in recent years. Rising interest rates have further elevated capital costs for producers. As a result, margins have been reduced across the board, impacting operations at each stage of the value chain. During periods of weak prices, these factors led some producers across many commodities to reduce or defer spending on mines as well as midstream assets.

Increasingly stringent environmental, social and governance (ESG) requirements have also influenced project costs in some advanced economies, making these assets less competitive compared with those in countries with lower regulatory standards.

Although the volatile, cyclical nature of commodity prices is well understood by market participants, the policy focus on ramping up the supply of critical minerals for the energy transition has been challenged by record price volatilty and persistent supply chain disruptions. Investors and producers have thus been reluctant to commit to large projects without sufficient confidence in the long-term business case for new and more diversified assets.

The lack of transparent pricing for many minerals contributes to this uncertainty. Although price discovery for metals such as nickel and copper takes place on liquid exchanges, pricing of lithium, cobalt and graphite, among other materials, still relies upon bilateral contracts that are surveyed and reported by price reporting agencies (PRAs) (see section on market transparency). Uncertainty over capital costs exacerbates the challenges facing project developers. For instance, in recent years, several lithium raw material development projects experienced a more than 50% increase in estimated capital intensity between pre-feasibility studies or preliminary economic assessments, and definitive feasibility studies.

Diversified refining and processing projects face additional challenges due to their limited pricing power, especially for non-integrated assets, relative to powerful incumbents. Positioned between the raw materials and the downstream value chain, projects are exposed to a cost and revenue squeeze and need to navigate the price volatility between raw material prices and downstream component prices. Price hedging has often proved challenging in relatively small and illiquid markets. Many projects being developed in geographically diverse regions have a higher-cost profile than those in today's dominant regions: for example, several coated spherical graphite projects under development in advanced economies have more than twice the capital intensity of those in the People's Republic of China (hereafter "China"). Without specific government measures to reinforce the investment case, consumers and investors typically do not assign much value to diversification, so such projects often face major challenges in mobilising the necessary capital. Moreover, many companies that aim to develop new refining and processing projects in diversified regions are small in size with limited track records, making it challenging to mobilise debt financing at affordable rates.

Government investment vehicles

Governments can intervene in various ways to help finance more diversified value chains. These interventions can come from four main sources: government departments and policy banks, sovereign wealth funds (SWF), development finance institutions (DFI), and export credit/insurance agencies (ECA). These agencies may engage directly with private sector firms, through state-owned or backed enterprises, in a hybrid fashion, or in partnership with foreign counterparts. They have a number of policy options available to them that range from direct debt or equity investments to indirect financial support and de-risking measures that boost competitiveness.

While there are often significant overlaps in the remits and capabilities of many of these institutions, they are differentiated in their strategic focus, risk tolerance, and the time horizon of their investment decision-making, as outlined in the table at the end of this section. The support they provide can be either in the form of capital expenditure (capex) financing, operating expense (opex) support, and/or risk mitigation.

Capex financing support

The vast majority of financial support mechanisms for the critical minerals sector have focused on large upfront capital expenditures. These include finance for the construction of mines, refineries and processing plants, and factories. These transactions, like those in the private sector, can contribute to various parts of the capital stack – as loans, equity stakes, or grants.

In the United States, the Department of Energy Loan Programs Office (LPO) has to date authorised more than USD 5 billion in conditional loan commitments for domestic minerals projects. Among these, the USD 2.26 billion conditional loan for Lithium Americas' Thacker Pass mine is the largest public commitment for a single project.

The French government, through the General Secretariat for Investment (SGPI), invested EUR 500 million as the anchor investor in a EUR 2 billion critical minerals fund managed by InfraVia, an infrastructure asset manager. In contrast to the approach taken by the US LPO and International Development Finance Corporation (DFC), which has invested directly in specific projects and companies, this investment relies on the external fund manager to identify the opportunity set and capitalise on them in alignment with French government policy.

Opex support

In addition to capex support, opex support measures are also adopted in ensuring the long-term bankability of projects given the decades-long investment horizons associated with planning, operating, and decommissioning. By lowering operating costs associated with mineral extraction and processing and helping stabilise long-term cash flows, higher-cost operations can improve economic competitiveness, thus helping the aim of diversification.

One of the most prominent policy initiatives for supply chain diversification is the Inflation Reduction Act (IRA) in the United States. The use of various tax credits on both the supply and demand sides have led to significant investment in the downstream domestic supply chain as well as the formation of agreements with free-trade agreement-compliant upstream suppliers. In addition to investment support through capital cost tax credits (48C), there are also production cost credits (45X) which provide 10% production tax credit for critical mineral processors. These forms of opex support can be effective in improving the business case to stimulate new investment, but require more policy commitment as they incur sustained financial burden over the long term.

Despite the attractiveness and importance of ongoing financial support mechanisms, their long-term nature also makes them more sensitive to political headwinds. This is in contrast to direct capex financing mechanisms, where committed loans and disbursements cannot easily be clawed back after a change in administration.

Risk mitigation and ancillary services

A third group of financial measures comprises options that are intended to de-risk investments and crowd in other investors, rather than directly subsidising or financing projects. Common strategies include offering loan guarantees to reduce the financial risk for private investors by providing a sovereign backstop, insuring transactions against counterparty risks that may not be available at a reasonable rate from commercial insurers, and directly lowering the cost of debt by bridging the gap between rates available to public institutions and the firm or project seeking funding.

These services are often offered by ECAs, which typically have expertise in risks associated with complex, multi-jurisdictional projects, in addition to or as an alternative to direct financing options.

For instance, the Korean Export and Import Bank, as part of the government's five-year plan to support battery supply chains, has increased the maximum loan size from 40% of the owner's equity to 50%, in addition to a preferential rate up to 120 basis points (bps) lower. Furthermore, the Korea Trade Insurance Corporation has announced an insurance policy discount of up to 20% in addition to increases in loan guarantees available.

In 2022, Canada's Critical Minerals Strategy introduced the 30% Critical Mineral Exploration Tax Credit (CMETC) aimed at helping companies raise equity capital by incentivising investors with tax benefits associated with flow-through shares. This functions by allowing investors to claim a tax deduction equivalent to a portion of exploration expenditures incurred by the company.

The CMETC acts in parallel with, but cannot be claimed in addition to, the existing Mineral Exploration Tax Credit (METC) of 15%. The METC, originally set to expire in March 2024, was extended to March 2025. The Prospectors and Developers Association of Canada estimates that flow-through share financing contributes over 65% of the funds raised on Canadian stock exchanges for exploration across the country. These tax credits do not subsidise upstream companies directly, but serve to encourage equity investment during the high-risk exploration phase.

Policy implications

Many of these policy intervention tools (outlined in the table at the end of this section) are intended to support national or regional strategies to decrease the geographic concentration of critical mineral supply chains. This can involve developments in either domestic projects or foreign projects with strategically aligned states.

Government departments and policy banks typically focus their spending on domestic projects and firms. For those without domestic reserves, DFIs and ECAs are the preferred vehicle given their specific mandate for foreign transactions. SWFs and policy banks with broad investment mandates are not common in advanced economies seeking to diversify their critical minerals supply chains, but there are examples elsewhere. For example, the Saudi Public Investment Fund, which has a wide-ranging mandate to actively invest over the long term to maximise sustainable returns, has taken an active position in global critical mineral supply chains as a financier of domestic and foreign projects.

Financial support from public agencies and institutions not only directly supports investments in projects, but may also serve three important but indirect functions: intergovernmental policy signalling to mitigate potential geopolitical risks, crowding in private capital, and freeing up funds for redeployment.

Given the financial challenges associated with supply chain diversification, there are several aspects to consider when countries introduce policy intervention tools to support financing. First, cross-agency coordination. The multiple risks associated with mineral value chains – geopolitical, financial, environmental, etc. – mean that the expertise of various departments and agencies is required to ensure that investments meet domestic and international guidelines. Furthermore, investment mandates of agencies such as government policy banks and DFIs often overlap but without a specific mandate to focus on mineral security. Coordination and information sharing between agencies can contribute to strategic alignment, ensuring efficient allocation of resources.

Second, tailored, fit-for-purpose investments. Given the numerous policy options available, investments in critical mineral supply chains should be tailored to meet specific strategic objectives, such as reducing import dependency, improving environmental sustainability, and ensuring the economic viability of domestic resources. A wide range of investment structures should be evaluated for their ability to address the unique risks at each stage of the supply chain.

Finally, financial incentives should aim to be synergistic across the whole value chain, rather than focusing narrowly on one sector. In particular, midstream processing of mined material into intermediate products is often lacking the support seen for end-use sectors.

While different public agencies and vehicles have distinct strengths and remits, political co-ordination is important in ensuring synergistic efforts

Public institutions and vehicles that play a role in financially supporting critical minerals value chains

	Ministries and programmes	Sovereign wealth funds	Development finance institutions	Export credit and insurance agencies
Description	Government departments that develop, implement, and finance policies	State-owned investment funds designed to manage and invest national wealth	Organisations that provide financial support and expertise to development projects, often focused on EMDE	Financial institutions that support national exports and facilitate international trade and investment
Relative risk tolerance	**Low-medium:** political questions on public finances lead to greater scrutiny	**Medium-high:** asset allocation strategies consider potential for higher returns	**Medium:** EMDE investments are associated with higher expected loss rates	**Low:** safeguarding domestic export industries is the priority, not returns
Key use case	**Policy alignment and direct financial support**: aligning industrial policies with national strategies via broad-based domestic investment, including in non-industry sectors	**Long-term investment in strategic assets:** investing in domestic and international projects across the value chain as part of a diversified asset portfolio	**Achieving co-benefits in the minerals sector:** advancing more socially and environmentally responsible supply chains that also contribute to policy priorities	**Export facilitation and trade financing**: assisting domestic companies in competing internationally, securing supply chains, and accessing new markets
Examples of institutions	DOE LPO (US)	Public Investment Fund (Saudi Arabia), Minerals Income Investment Fund (Ghana)	KfW (Germany), US DFC, IFC	Export Finance Australia (Australia), K-Sure (Korea)

Note: EMDE = emerging market and developing economies; DOE = Department of Energy; IFC = International Finance Corporation.

A range of policy options can be deployed to address various financing challenges associated with each segment of the value chain

Financial policy options available for promoting investment in critical mineral supply chains

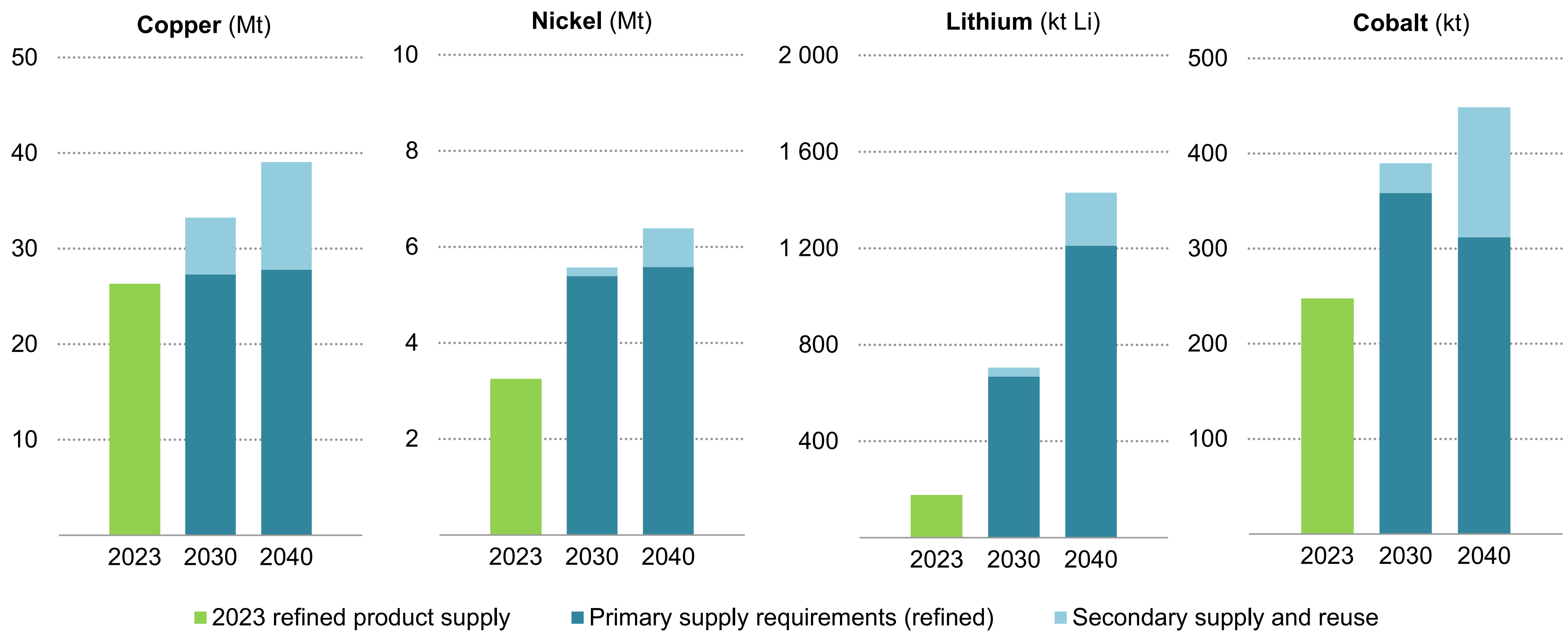
		Policy option	Description	Typical size (USD million)	Examples
Capex financing	1	**Grants**	Non-repayable awards, usually to support capital projects	1-100	Australia: International Partnerships in Critical Minerals Grants (AUD 40 million) US: DoD grants to Albermarle for lithium production (USD 90 million) and processing plants (USD 150 million)
	2	**Concessional loans**	Loans with favourable rates and/or repayment terms	100-1 000	US: DOE LPO loan to Lithium Americas (USD 2.26 billion)
	3	**Equity investments**	Taking stakes in key minerals projects with risk-sharing	10-100	France: SGPI investment in equity fund (EUR 500 million) US: DFC stake in TechMet (USD 75 million) Germany: KfW raw materials fund (EUR 1 billion)
Opex support	4	**Tax credits**	Reductions in tax liability in exchange for investment or production targets	N/A	US: Inflation Reduction Act 45X (10% of production cost)
	5	**Reduced royalties**	Increasing the operating income margin of the asset		Australia: Western Australia nickel royalty assistance programme (50% rebate for 18 months)
Risk mitigation	6	**Loan guarantees**	Sovereign guarantees on private loans to reduce lender risk	10-100	Canada: Indigenous loan guarantee programme (CAD 5 billion)
	7	**Insurance products**	Protection against risks that may not be covered by commercial insurers	10-100	Japan: Loan insurance for procurement and equity investment
	8	**Interest rate reduction**	Directly lowering the cost of debt for borrowers	N/A	Korea: KEXIM to lower rates for strategic industries, including batteries, by up to 120 bps

Note: AUD = Australian dollars; DoD = Department of Defense; KEXIM = Korea Export-Import Bank.

Recycling, innovation, and behavioural change

Recycled volumes from manufacturing scrap and end-of-life equipment contribute to reducing the requirements for primary supply

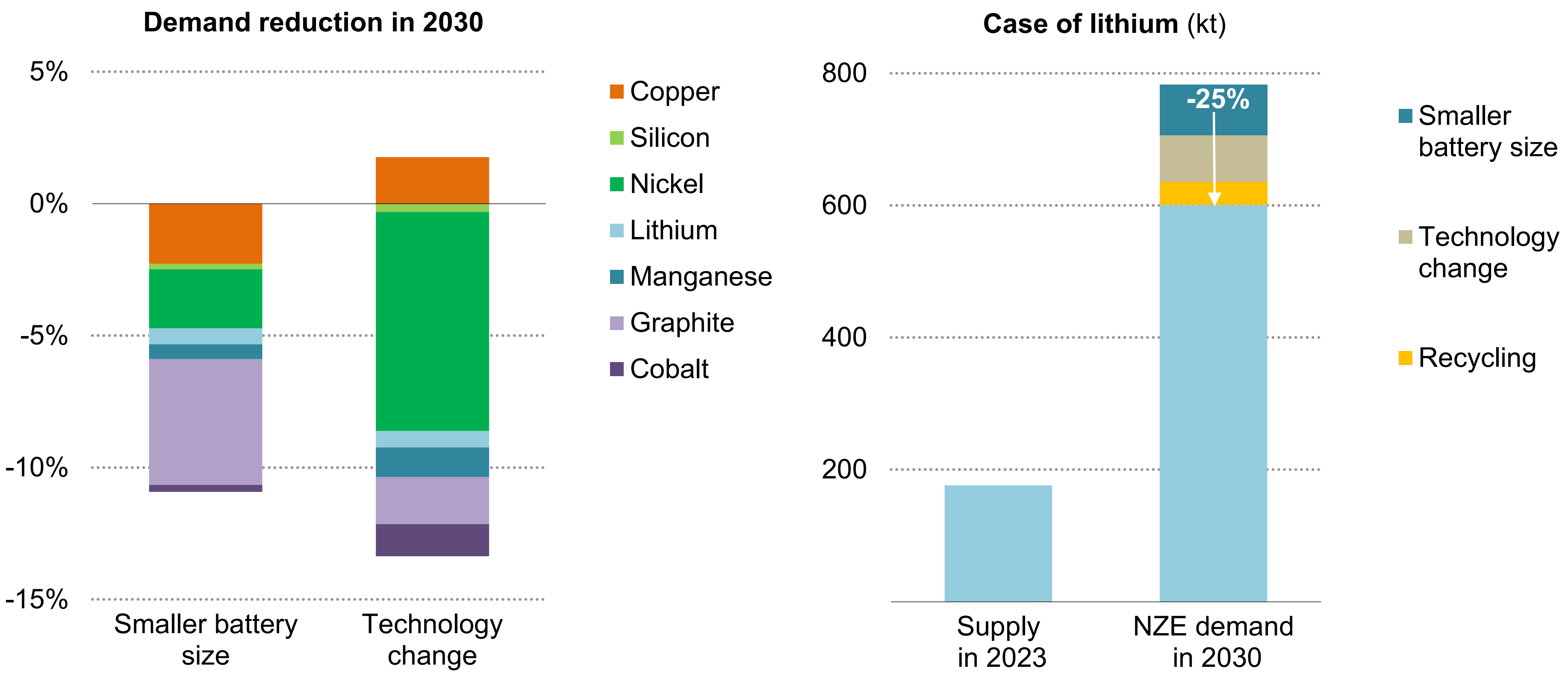
Primary supply requirements and projected secondary supply for selected minerals in the NZE Scenario



Note: Secondary supply of copper does not include direct use of scrap.

Technology innovation and demand-side measures can play significant roles in reducing mineral demand

Mineral demand reduction potential for electric vehicle batteries and battery storage, 2030



Note: Technology change assumes a higher share of lithium-ion phosphate chemistries and sodium-ion batteries.

Scaling up recycling, continued investment in technology innovation, and promoting consumer behavioural changes play a crucial role in ensuring the security of mineral supplies

Every country's strategy on critical minerals will inevitably reflect its specific circumstances, but it would be a mistake for such strategies to focus only on increased exploration, mining and refining investment. A comprehensive approach to security and sustainability of supply needs to also address the demand side of the equation, which plays a crucial role in narrowing supply-demand gaps while simultaneously mitigating the potential environmental and social harms associated with resource extraction and use. This encompasses elements such as innovation, recycling, behavioural measures and rigorous sustainability standards. The importance of unlocking the power of technology and recycling has long been a theme of IEA analysis and this was one of the key takeaways from the first-ever IEA Critical Minerals and Clean Energy Summit in September 2023[1].

Recycling

Recycling creates a secondary supply of minerals that relieves the pressure on primary supply from mining and refining. A strong focus on recycling can deliver triple benefits: complementing primary mineral supplies, improving security of supply for regions with limited resource endowments and enhancing environmental performance and waste management.

For base metals such as aluminium, recycling practices are well established, but this is not yet the case for many energy transition minerals such as lithium, nickel (from electric vehicle [EV] and storage batteries) and rare earth elements (from wind turbines and EV motors). For battery metals, today's feedstock for recycling is dominated by electronic waste and scrap from manufacturing processes, but this is set to change by the end of the decade as the first generation of electric vehicles reach the end of their life. Globally, around 30 GWh of spent electric car batteries is expected to be available for recycling by the end of the decade.

While recycling would not eliminate the need for continued investment in new supplies, we estimate that by 2040, recycled quantities of copper, lithium, nickel and cobalt from clean energy applications could reduce primary supply requirements for key minerals by 10-30%. The security benefits of recycling can be far

[1] The IEA will delve deeper into the topic of recycling – covering various topics such as battery recycling, industrial scrap and mine waste – in a forthcoming report for the Italian G7 presidency.

greater for regions with wider deployment of clean energy technologies due to greater economies of scale. A strong example of the environmental benefits comes from the aluminium industry, where recycling of post-consumer scrap has been shown to reduce emissions by 90% compared with primary aluminium. Furthermore, recent studies show that total GHG emissions for manufacturing a nickel-rich lithium-ion battery cell can be around 28% lower if made from recycled materials rather than virgin minerals.

Recovering minerals from mine waste, also known as tailings reprocessing, is a growing area of interest. As ore grades decline, larger amounts of wastes are generated during mining, increasing the economic and environmental cost of tailings management. Advancements in processing technologies mean that some tailings have grades comparable to currently economical ore deposits. Thus, reprocessing can have various benefits: revenue opportunities, water recovery and environmental impact mitigation.

Technology and innovation

Technology advances also have a major role in alleviating potential supply strains. For example, significant reductions in the use of silver and silicon in solar cells over the past decade have contributed to a spectacular rise in deployment of solar PV. For grids, our projections indicate that deploying high-voltage direct current transmission lines more widely in electricity networks has the potential to shrink their material demand by 3% in 2030 and 10% in 2050. Similarly, a sensitivity case covering an accelerated global adoption of lithium-iron phosphate chemistries and sodium-ion batteries could reduce mineral demand for EV batteries by around 13% in 2030 and 18% in 2050 compared to the NZE Scenario's base case.

Behavioural changes

Energy demand depends on the behavioural choices of millions of consumers worldwide. Behavioural changes are actions that energy consumers take to reduce wasteful or unnecessary energy consumption. Many of these changes take place as part of daily life, and involve using energy differently or using less of it. These changes depend in part on individual choices and evolving socio-cultural norms. However, it is systemic transformations brought about by targeted and well-designed policy interventions that count most in changing consumer behaviour, and these often depend on the availability of infrastructure of one kind or another.

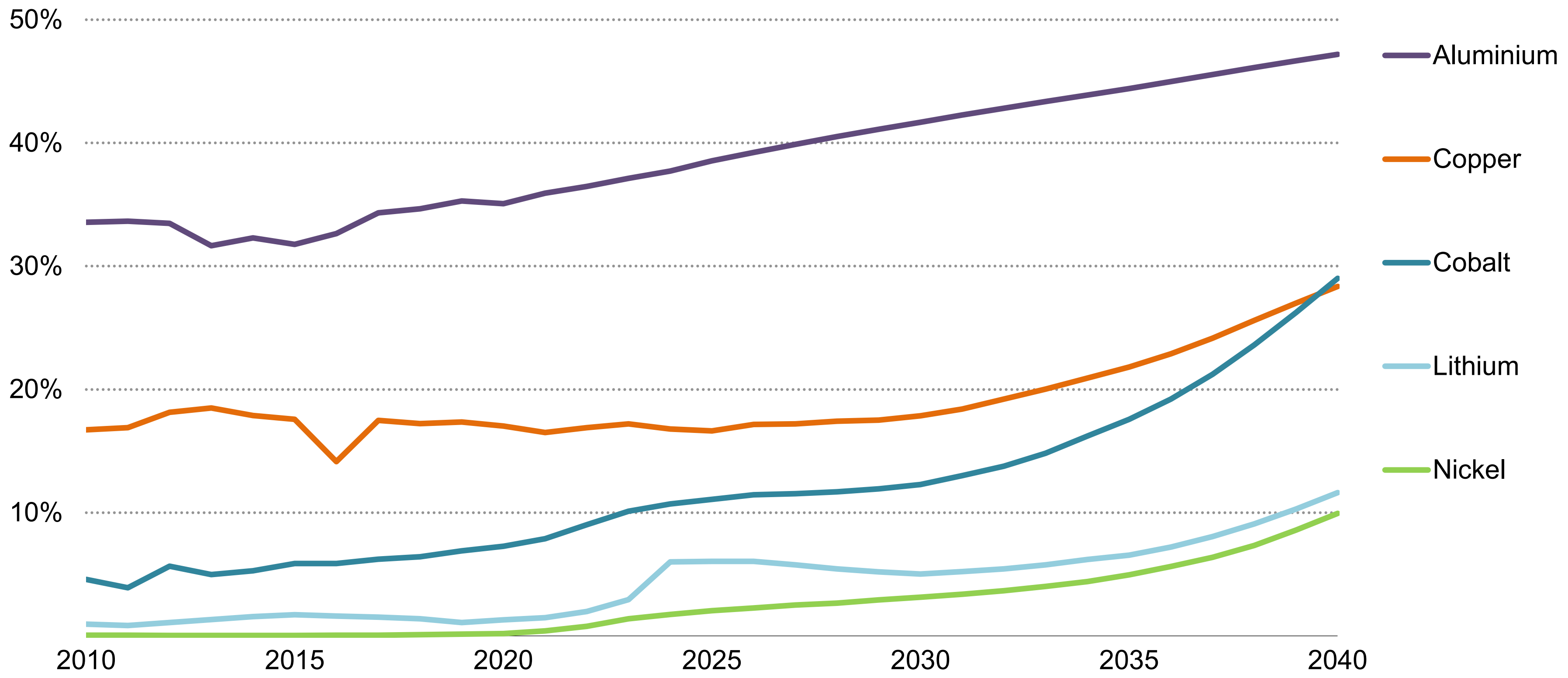
Behavioural changes in the NZE Scenario help to bring about a more equitable and just energy transition. But in terms of critical minerals, behavioural changes can also imply a more tempered demand that can help narrow the demand-supply gap, especially changes in behaviour related to transport needs.

In 2022, electric SUVs accounted for over half of global electric car sales for the first time ever and took up 16% of total SUV sales. Such a consumer preference is contributing to a further increase in mineral demand as SUVs require larger batteries to power them. Behavioural changes and targeted measures to tame the appetite for SUVs and other large vehicles could result in considerable demand reduction for battery metals. IEA projections based on these specific sensitivity cases show that measures to promote smaller electric cars lead to a more than 10% reduction in battery mineral demand by 2030 projected in the NZE Scenario, compared with a counterfactual case where SUV demand continues to grow. In February 2024, the city of Paris took measures to moderate the average size of cars on the roads by voting for elevated parking tariffs for larger private vehicles. Other behavioural measures that can reduce car traffic and thereby, not just gasoline demand from internal combustion engine vehicles but also demand for battery metals for EVs, include increased share of carpooling, active modes of transportation and public transit in total road passenger transport.

The IEA recently showed that, in the case of lithium, the combination of smaller EV battery sizes, alternative chemistries and recycling could reduce demand for lithium by 25% in 2030 in the NZE Scenario, saving an amount similar to today's production volumes. With these reductions, new supplies would need to grow by 20% per year between today and 2030. The lithium industry managed to deliver this scale of growth in recent years. For example, lithium raw material supply grew by roughly 20% per year over the past five years.

Recycling rates for many materials have exhibited limited growth in the past, but growing policy attention and the rise of battery recycling are set to change the picture

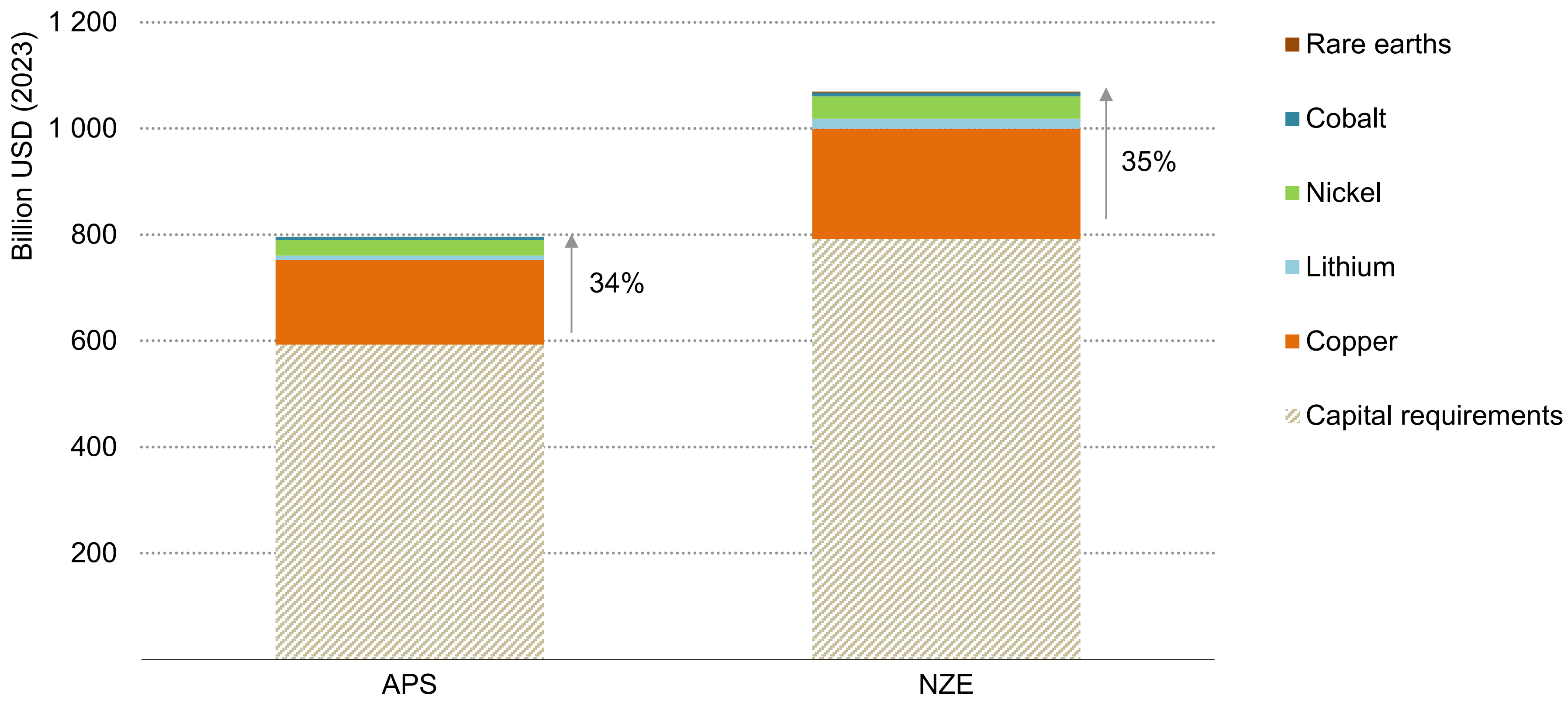
Share of secondary supply in total demand for selected materials in the NZE Scenario



Note: Secondary supply of copper excludes direct use of scrap.

Without the uptake of recycling and reuse, mining capital requirements to meet demand would have been a third higher

Reduced mining capital requirements due to higher recycling and reuse in the APS and NZE Scenario



Much stronger efforts are needed to scale up recycling and ease the strains on mineral supply in a net zero pathway

Global battery recycling capacity surpassed 300 GWh in 2023, of which more than 80% was located in China, far ahead of Europe and the United States with under 2% each. Many technology developers and industry actors are seeking to position themselves in the future market for end-of-life EV management and have announced considerable capacity expansions. If all announced projects are developed in full and on time, global battery recycling capacity could exceed 1 500 GWh in 2030, of which 70% is in China, and about 10% each in Europe and the United States. The main sources of supply for battery recycling plants in 2030 will be EV battery production scrap, accounting for half of supply, and retired EV batteries, accounting for about 20%. From 2030, end-of-life batteries surpass manufacturing scrap as the primary source of recycling.

Policy measures, including standardisation and alignment of battery waste and transportation codes (e.g. for black mass handling and cross-border transport to high-quality recyclers), the implementation of extended producer responsibility principles for EV batteries, the development of comprehensive collection infrastructure, and the initiation of information and communication campaigns, all play pivotal roles in encouraging the uptake of battery recycling.

Despite the undeniably significant role of batteries in total mineral demand, as the clean energy transition ramps up in almost every major region, recycling efforts will need to extend to technologies beyond batteries as well. In addition to scaling up recycling infrastructure, efforts also need to be directed towards the maintenance and repair of products that will enable longer use.

The share of secondary supply in mineral demand has remained fairly stable for the last decade, but this changes rapidly in the NZE Scenario. The share of secondary supply for nickel needs to grow from around 1% today to 3% in 2030, and that of lithium from 3% to 5% in the same period. By 2040, secondary supply share of most major critical minerals would need to reach at least 15% under the NZE Scenario.

If the share of secondary supply were to stay at today's levels, capital requirements for mining to meet demand in climate-driven scenarios would have been a third higher, highlighting the significance of recycling in alleviating pressure on primary supply.

Policies and actions to mitigate increases in demand for critical minerals

Policy area	Description	Examples
Repair, refurbishment and remanufacturing	Extending product lifetimes, reducing the need for new production	• Siemens Gamesa's lifetime extension programme for wind turbines
Recycling	Collecting, processing, and reusing materials that would otherwise be discarded as waste	• Minimum recycled content requirements, extended producer responsibility regulations
Substitution	Replacing materials with renewable or more sustainable alternatives	• Chemistry change for EV batteries • Adoption of alternative battery technologies
Material efficiency	Designing products and processes to minimise material use, waste, and environmental impact	• Iridium loading reduction in proton exchange membrane electrolyser manufacturing • Reduced silicon use in solar PV
Product-as-a-Service	Business models that provide services instead of selling products	• Vehicle-sharing schemes to increase utilisation of assets
Behavioural changes	Encouraging individuals to adopt more sustainable habits and practices such as reducing consumption	• Opting for optimal size vehicles than larger cars • Reducing private car journeys via public transport

Market transparency

Market transparency brings important benefits to all aspects of the supply chain

Despite strong expected increases in demand, market transparency of commodities such as cobalt, lithium, and rare earth elements remains limited, challenging price-hedging and discouraging investment and risk assessments. Market transparency covers both the question of **pricing** – including efficient market price discovery mechanisms and financial tools to hedge price risks – and **information** – the importance of publicly available data on consumption, supply, inventories, trade and ESG performance.

Transparency of pricing and market information brings important benefits to all aspects of the supply chain: producers and consumers are able to hedge their price risk, plan their stocks and production, and negotiate fair contracts. Merchants and intermediaries are able to correct global supply and demand imbalances as efficiently as possible. Governments benefit by being able to plan ahead and ensure supply continuity. Information transparency enables the anticipation of potential risk areas, allowing policymakers to target support where it is most needed.

Price transparency: Tailoring actions to each critical mineral's market maturity level

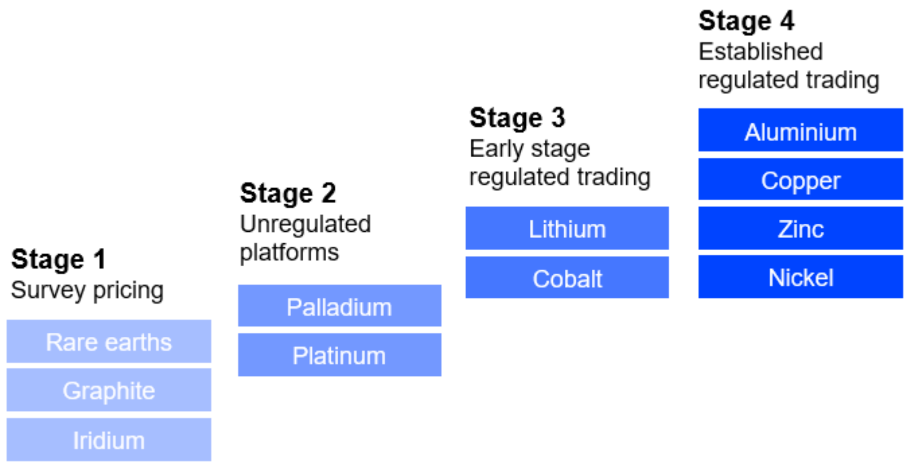
The primary element of a well-functioning market for minerals and metals is transparency of pricing. Efficient price discovery processes provide two main benefits to the market: first, they offer clearer market signals, aiding informed investment decisions; second, they facilitate the development of financial tools to mitigate risks, allowing for hedging by midstream operators (refining, recycling) and downstream consumers.

In a developed, sophisticated market, this means that there is a clear "spot" price (i.e. for immediate delivery), as well as a futures price curve – i.e. information about prices for delivery months or years into the future. While some commodities such as copper and aluminium already benefit from established and regulated exchanges with ample liquidity, not all critical minerals benefit from such levels of market maturity. Many of their markets contend with market concentration, insufficient liquidity, and reliance on bilateral contracts.

There are broadly four stages of development in price transparency. Some commodities, such as copper and nickel, are already traded on regulated exchanges, where both spot and future contracts can be publicly traded – but derivatives can also often be traded outside of these exchanges, as over-the-counter (OTC) forward contracts, where prices are less easily tracked (see figure below – "Stage 4. Established and regulated trading"). For others, such as lithium and cobalt, there are signs of growing trade activities at major exchanges, while remaining significantly less liquid ("Stage 3. Early-stage regulated trading"). Although traded derivatives markets are important in assessing market participants' expectations, OTC financial contracts are of particular utility in risk management, as they allow more effective price hedging.

For the less liquid markets, market players rely on unregulated spot auction platforms ("Stage 2") or surveys from price reporting agencies (PRAs) ("Stage 1") or other key market actors, who may – or may not – meet the principles set out by the International Organization of Securities Commissions (IOSCO). The different stages of market maturity discussed here are indicative, and each element may face different circumstances.

Market maturity levels for selected minerals



Price data are often much more limited for midstream processing than refined material. While for some commodities, such as copper, "treatment and refining charges" (the amount mines need to pay to smelt concentrate into cathodes) are tracked by agencies, data are less available for other commodities. The absence of data on refining costs and prices, as well as existing capacities and stockpiles, restricts further investments in midstream capacities, and thus their diversification.

Some of the smaller commodities may have structurally insufficient liquidity pools for market-based price discovery mechanisms. In these cases, policymakers could consider various ways to incentivise or encourage contributions by market participants to PRAs' platforms who adhere to the IOSCO principles or their equivalents, or to enhance data collection from businesses. Regulated markets also require deep liquidity pools for effective price discovery. In this context, governments could avoid actions that would further fragment liquidity pools. For cobalt and lithium in particular, there is a question as to whether physically-deliverable contracts could be possible. This would have the advantage of providing stocks data to the market, which gives some proxy data to the market as to supply and demand.

Finally, there is a growing interest in pricing schemes that incorporate ESG performance. While many PRAs are introducing new price indices, it is uncertain whether these indices would achieve sufficient liquidity without policy and regulatory support to encourage consumers to consider sustainability aspects in their procurement decisions.

Classification of commodity markets by maturity level

	Stage 1	Stage 2	Stage 3	Stage 4
	Survey pricing	**Unregulated platforms**	**Early stage regulated trading**	**Established and regulated trading**
Price discovery mechanism	PRAs and market participants	PRAs and trading platform	Exchange	Exchange
Reporting frequency	Monthly	Weekly-daily	Instant	Instant
Risk management tools	Limited to bilateral agreements	Futures and options with financial inter-mediaries	Traded futures and options	Active derivative markets
Examples	Rare earth elements, graphite	Platinum, palladium	Lithium, cobalt	Aluminium, copper, zinc, nickel

Market information transparency

Understanding critical mineral production and refining also relies both on public data and on mining and supply chain actors, with multiple benefits: allowing more informed investment decisions, facilitating supply risk identification along the supply chain, enabling systematic tracking of ESG performance, informing due diligence efforts, facilitating audit and verification of claims and ensuring better accountability.

However, information transparency faces significant challenges – insufficient publicly available data, particularly on the midstream, underlaid by a lack of consensus on what data could or should be shared through the supply chain, and further disclosed to the public and consumers.

Some nations already disclose significant data on mining volumes, given the economic and social importance of this activity in their jurisdictions. Stock exchanges and their regulators, particularly in Canada (NI National Instrument 43-101 Standards of Disclosure for Mineral Projects) and Australia (Joint Ore Reserves Committee [JORC] reporting code), have also played a crucial role in making more data on production and reserves of publicly traded mining companies accessible.

Public data initiatives have the potential to offer valuable insights to stakeholders in the market. While some disclosures have been made under the Extractive Industries Transparency Initiative (EITI), countries do not necessarily systematically disclose the information even if it is required under EITI. In addition to private disclosures from publicly traded companies, efforts are underway to classify and make data on resources more readily available, often held by geological surveys, with the United Nations Framework Classification for Resources (UNFC).

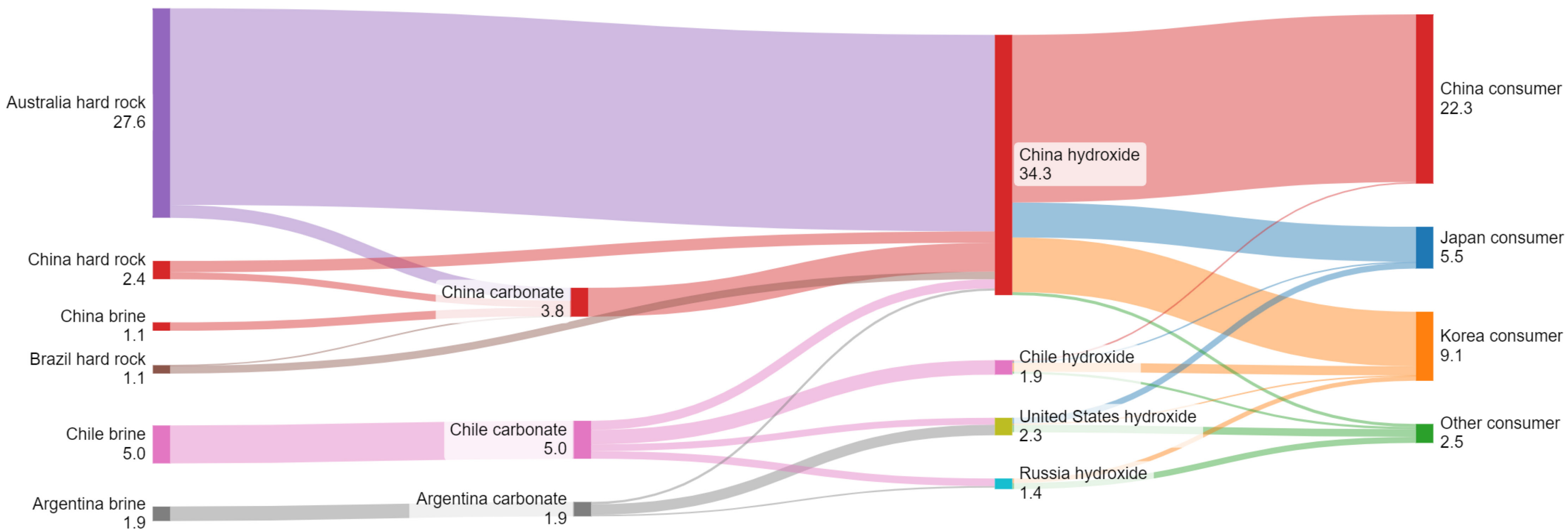
For refining and trade, public statistics face challenges in portraying what is now becoming an essential section of many economies – even though they play a critical role in understanding complex supply chains. In particular, the Harmonised System (HS) codes can facilitate access to trade data for materials of growing importance. However, key commodities such as lithium ore, concentrate and chemicals or cobalt and manganese sulphates, essential to the EV battery, do not yet have harmonised codes, hindering efficient tracking of trade flows.

Likewise, information about regional consumption is relatively lacking compared with production volumes, which hampers the granular understanding of market balances. All of these underscore the necessity of launching efforts to systematically collect reliable data consistently, beginning with identifying areas where publicly available data are most lacking.

Traceability tools can also be a technical enabler, though not an end goal in themselves. There is a growing interest in decentralised databases, but the underlying challenge often lies in defining i) which data should be shared to achieve transparency objectives, in what frequency; ii) with whom this data should be shared; iii) how accountable data producers are; and iv) whether public enforcement is necessary to provide adequate incentives and ensure adherence to best practices.

Trade analysis is key to identifying bottlenecks in complex supply chains

Lithium hydroxide supply chain, 2021



Notes: Values in kt of elemental Li. Lithium hydroxide supply chain includes trade of lithium-containing commodities (carbonates, ore concentrates) used as inputs for hydroxide production.

Sources: IEA analysis, based on UN Comtrade and Wood Mackenzie.

There is scope to improve codes for trade reporting to better track trade flows of raw and refined materials

World Customs Organization HS codes for criticial mineral trades

	Copper	Lithium	Nickel	Cobalt	Graphite	Rare earth elements	Manganese
Mined	2603.00 ("Copper ores and concentrates")	Included in 2530.90 ("Mineral substances not elsewhere specified or included")	2604.00 ("Nickel ores and concentrates")	2605.00 ("Cobalt ores and concentrates")	2504.10 and 2504.90 ("Natural graphite")	Included in 2530.90 ("Mineral substances not elsewhere specified or included")	2602.00 ("Manganese ores and concentrates")
Processed	2825.50, 2827.41, 2833.25 (copper chemicals) and the complete 74 chapter ("Copper and articles thereof")	2825.20 (Li oxide and hydroxide) 2836.91 (Li carbonates), also included in 2805.19 ("Alkali metals, including lithium metal"), 2833.29 ("Sulphates") and 2827.39 ("other chlorides")	2825.40, 2827.35, 2833.24 (Nickel chemicals), 7202.60 (Ferronickel) and the complete 75 chapter ("Nickel and articles thereof")	2822.00 (Co oxides and hydroxides), 8105.20 (Co mattes) and also included in 2833.29 ("Sulphates")	3801.1 (synthetic graphite) and 3801.2 (natural graphite)	2805.30, 2846.10, 2846.90	2820.10, 2820.90 (manganese oxide and dioxide), 7202.11, 7202.19 (ferro-manganese), 8111.00 (manganese metal) and also included in 2833.29 (sulphates)
Secondary (waste, scrap...)	7404.00 ("Cu waste and scrap")		7503.00 ("Ni waste and scrap")	8105.30 ("Co waste and scrap")			Manganese waste and scrap is also included in 8111.00
Notes		EU imports lithium ores under domestic code 25309040, China uses a ten-digit code for various lithium ores (2530909902 for spodumene…)			No distinction between raw and refined battery-grade graphite in the HS code system.	EU imports rare earth ores under domestic code 25309050, China under domestic code 25309020.	

Sustainable and responsible supplies

Critical minerals cannot be truly secure, reliable and resilient unless they are also sustainably and responsibly produced

The foremost reason to address the ESG risks within the mineral supply chain is to protect people, communities and the environment. Robust efforts to ensure that supply chains are responsible and sustainable will be necessary to ensure that energy transitions are people-centred and that the benefits associated with mineral production, such as revenue and jobs, are captured in producer countries and communities. In parallel, improving the ESG performance of mineral supply chains can yield important security-of-supply benefits.

In fact, without serious efforts to mitigate the ESG risks associated with mineral supply chains, there may not be sufficient supplies to support the rapid scale-up of clean energy technologies that is needed to reach climate goals and to avert the worst effects of climate change. Governments and companies alike have a role in developing sustainable and responsible supply chains. While companies may champion sustainable and responsible practices and transparently monitor progress, governments play a crucial role in incentivising corporate action and creating a regulatory environment conducive to high ESG standards.

While there are many ESG risks that can lead to supply disruptions, we have identified six priority areas that have particularly important implications for security of supply: water, GHG emissions, biodiversity, human rights, communities and corruption. Each of these risks impacts security of supply in a different way, but broadly, failures in these areas can limit market access, create legal barriers, discourage investment, damage reputation, increase the likelihood of opposition from local communities, and in some cases physically prevent projects from operating.

Critical minerals are often situated in regions characterised by elevated water stress. Developing infrastructure that ensures secure water access for local communities can help companies prevent conflicts where water access is limited. Policy responses that encourage water stewardship include conditioning public investment to or establishing specific targets for water quality, use and effluents that improve over time.

Companies that do not reduce and report GHG emissions face risks to market access and their reputation. Corporate reporting can build onto existing standards and external verification to provide transparent and credible data. Investment in on-site renewables and energy efficiency can help drive decarbonisation efforts. Governments can improve or expand GHG reporting requirements and ensure that data on emissions are publicly available.

Operations that fail to address biodiversity impacts may face regulatory barriers and reputational and investment risks – especially for mineral deposits located in key biodiversity areas. Companies can minimise land use and related impacts by working on project design and implementing technologies tailored to each site. Governments can strengthen biodiversity protections in mining regulations and permits and improve monitoring and disclosure of biodiversity data.

Enhancing human rights standards in mining operations can mitigate operational disruptions and reduce divestment resulting from human rights violations, including child labour and forced labour. Corporations and governments can enable supply chain transparency by embedding human rights risks in due diligence systems or regulatory frameworks, while supporting the continued implementation and enforcement of protections.

Meaningful engagement with local communities and Indigenous Peoples can help projects obtain and maintain a social licence to operate. This rests on credible local community and Indigenous Peoples-led consultation schemes. Free, prior and informed consent of Indigenous Peoples and potentially impacted communities is a best practice, where not already required by law.

Reducing corruption and governance risks can facilitate investment and strengthen public confidence in mining operations. This can be supported by targeted policies and the disclosure of permits, licences, and contracts; company beneficial ownership; and payments to governments.

Considering the available levers for action, we have developed five key recommendations for policy makers to ensure that critical mineral value chains are sustainable and responsible:

- **Better regulations.** Ensure legal and regulatory protections for the environment, workers, Indigenous Peoples and communities, backed by sufficient means of implementation and enforcement.
- **Targeted public spending.** Channel public spending to encourage the development of better practices and to incentivise good performance.
- **Improved data.** Strengthen the collection and reporting of granular and standardised data to enable benchmarking and progress tracking throughout the supply chain.
- **Increased transparency.** Improve transparency throughout the supply chain, including by enhancing traceability, undertaking due diligence and reporting publicly on risks and mitigation actions.
- **Support sustainability standards.** Support the development of initiatives that help companies demonstrate that their operations are sustainable and responsible while ensuring cross-compatibility and interoperability.

Governments can play an important role in promoting improvements by incorporating the recommendations into their policy and investment decisions. These five recommendations are cross-cutting and can apply to all ESG risks

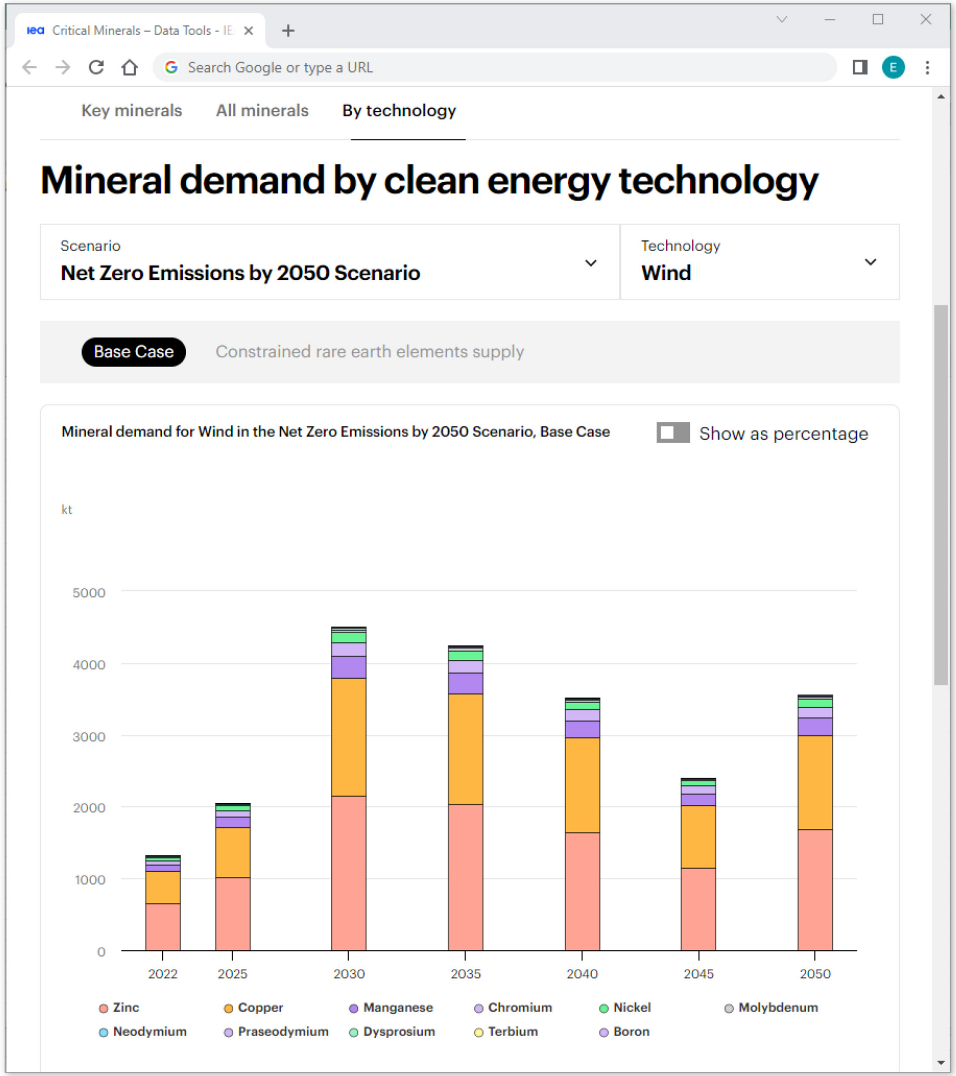
Annex

IEA Critical Minerals Data Explorer

The IEA has integrated critical minerals into its long-term energy modelling framework. Last year, alongside the Critical Minerals Market Review 2023, the IEA Critical Minerals Data Explorer was launched. The explorer is an interactive online tool that allows users to easily access the IEA's projection data. This year the data explorer has been updated to now include long-term supply projection data as well as demand projection data for the key energy transition minerals (copper, lithium, nickel, cobalt, graphite and rare earth elements).

The tool provides users with access to the IEA's demand projection results under various energy scenarios and technology evolution trends (through various alternative technology cases). Users can look up total demand for key energy transition minerals and projected mineral demand in the clean energy sector by technology and commodity, scenario and technology case. Long-term supply projections for the key energy transition minerals are now accessible in the tool. Supply projections are based on the project pipeline for each mineral in a base case and high production case based on the project's probablity of coming online.

The numbers are regularly updated to align with the latest energy projections.

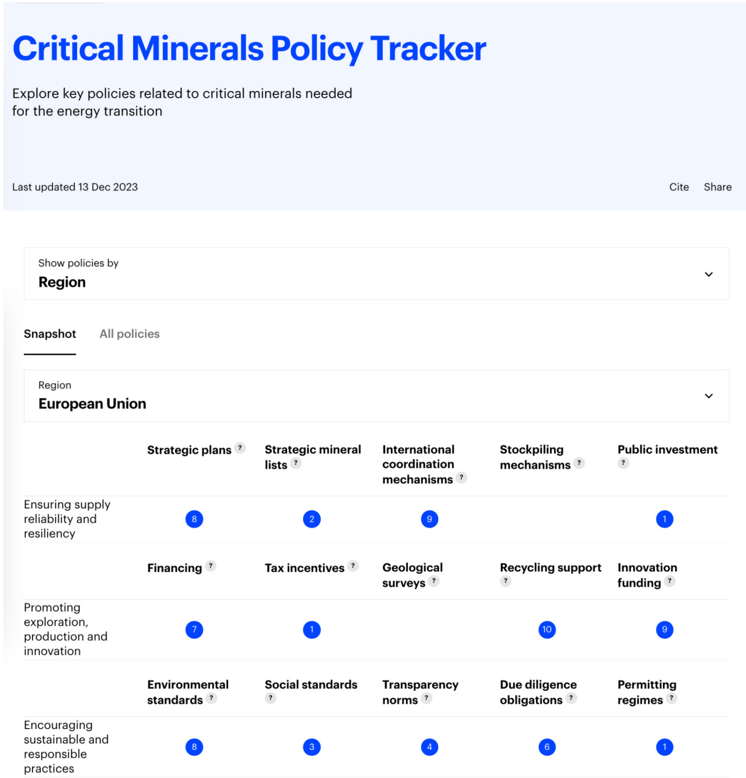


IEA Critical Minerals Policy Tracker

The IEA launched the Critical Minerals Policy Tracker in November 2022, which monitors and analyses the development of policies concerning critical minerals. This tool tracks policies across over 35 countries, starting from an initial dataset of 200 policies and expanded to 450 policies by 2023. Updated annually to ensure the inclusion of new policies and any amendments, the latest update was completed in December 2023. While not exhaustive, this data tool provides an overview of the evolving landscape in mineral supply chain governance in the context of clean energy transitions.

The data for the Tracker is primarily sourced from the IEA Policies Database, which encompasses an array of government-issued policies, laws, and regulations relevant to the energy sector. The methodology for data collection for the Critical Minerals Policy Tracker includes desk research and stakeholder submissions to capture policies in place within each of the focus countries and regions. For the 2023 update, a questionnaire was circulated among all IEA member countries via the IEA's Working Party on Critical Minerals. Feedback from country delegates and external researchers further refines and validates the database entries.

Policies tracked by this tool are categorised into three key areas: ensuring supply reliability and resiliency, promoting exploration, production, and innovation, and encouraging sustainable and responsible practices. Within each category, policies are further divided into five subcategories. This categorisation aids in the IEA's systematic analysis of policy trends and differences across various countries and regions, providing stakeholders with insights into the global policy approaches to managing critical mineral resources.



Methodology

Scope

The critical minerals model, added as a permanent module in the Global Energy and Climate (GEC) Model during the 2022 modelling cycle, assesses the mineral requirements for the following clean energy technologies:

- low-emissions power generation
  - solar PV (utility-scale and distributed)
  - wind (onshore and offshore)
  - concentrating solar power (parabolic troughs and central tower)
  - hydropower
  - geothermal
  - bioenergy for power
  - nuclear power
- electricity networks (transmission, distribution, and transformer)
- electric vehicles (battery electric and plug-in hybrid electric vehicles)
- battery storage (utility-scale and residential)
- hydrogen (electrolysers and fuel cells)

All of these energy technologies require metals and alloys, which are produced by processing mineral-containing ores. Ores – the raw, economically viable rocks that are mined – are beneficiated to liberate and concentrate the minerals of interest. Those minerals are further processed to extract the metals or alloys of interest. Processed metals and alloys are then used in end-use applications. While this analysis covers the entire mineral and metal value chain from mining to processing operations, we use "minerals" as a representative term for the sake of simplicity.

We focus specifically on the use of minerals in clean energy technologies, given that they generally require considerably more minerals than their fossil fuel counterparts. Our model also focuses on the requirements for building a plant (or making equipment) and not on operational requirements (e.g. uranium consumption in nuclear plants).

Our model considers a wide range of minerals used in clean energy technologies. They include copper, major battery metals (lithium, nickel, cobalt, manganese and graphite), rare earth elements, arsenic, boron, cadmium, chromium, gallium, germanium, hafnium, indium, iridium, lead, magnesium, molybdenum, niobium, platinum group metals, selenium, silicon, silver, tantalum, tellurium, tin, titanium, tungsten, vanadium and zinc.

Steel and aluminium are widely used across many clean energy technologies, but we have excluded them from the scope of this analysis. Steel does not have substantial security implications and the energy sector is not a major driver of growth in steel demand. Aluminium demand is assessed for electricity networks only as the outlook for copper is inherently linked with aluminium use in grid lines, but is not included in the aggregate demand projections.

For the six key energy transition minerals – copper, lithium, nickel, cobalt, graphite and rare earth elements – we model total demand including uses in clean energy applications and other segments. Consumption outside the clean energy sector has been estimated using historical consumption by end-use applications, relevant activity drivers (e.g. GDP, industry value added, steel production, etc.) and material intensities.

Demand

For each of the clean energy technologies, we estimate overall mineral demand using five main variables:

- clean energy deployment trends under different scenarios
- sub-technology shares within each technology area
- mineral intensity of each sub-technology
- mineral intensity improvements
- material efficiency measures (recycling, reuse and behavioural change)

Clean energy deployment trends under the Stated Policies Scenario (STEPS), the Announced Pledges Scenario (APS), and the Net Zero Emissions by 2050 (NZE) Scenario are taken from the projections from the World Energy Outlook 2023, adjusted by latest information from the Global EV Outlook 2024 and other sources.

Mineral intensity assumptions were developed through extensive literature review and expert and industry consultations, including with IEA Technology Collaboration Programmes. The pace of mineral intensity improvements varies by scenario, with the STEPS generally seeing minimal improvement over time as compared with modest improvement (around 10% in the longer term) assumed in the APS and NZE Scenario. In areas that may particularly benefit from economies of scale or technology improvement (e.g. silicon and silver use in solar PV, platinum loading in fuel cells, rare earth elements use in wind turbines, copper in buildings), specific improvement rates have been applied based on the review of underlying drivers.

Supply

For the six key energy transition minerals, primary supply requirements have been assessed by deducing projected secondary supply from projected total demand.

Secondary production is estimated with two parameters: the average recycling rate and the lifetime of each end-use sector. The recycling rate is the combination of the end-of-life collection rate (the amount of a certain product being collected for recycling) and the yield rate (the amount of material a recycling process can actually recover). For emerging technologies such as lithium-ion batteries, we assume collection rates increase at a faster pace. For batteries, the collection rates gradually increase from around 45% in the early-2020s to 80% by 2040 in the NZE Scenario. The yield rate is assumed to vary according to the technical limitations for the extraction of each mineral using the currently available recycling methods. The reuse rates are much lower than the collection rate for recycling as the use of second-life batteries (in grid applications) faces many technical and regulatory obstacles. Losses from manufacturing processes are also taken into account. For primary supply requirements for mined materials, a certain level of loss ratio during refining processes is assumed.

Supply projections for the key energy transition minerals are built using the data for the pipeline of operating and announced mining and refining projects by country. These projections are divided into a base case and a high production case, whose categorisation is assessed through their probability of coming online based on various factors such as the status of financing, permitting and feasibility studies.

We acknowledge the use of data on mining and refining projects from various professional information sources such as S&P Global Market Intelligence, Wood Mackenzie, Benchmark Mineral Intelligence, and Project Blue.

Mineral-specific clean energy transition risk assessment – detailed evaluation criteria

Supply risks	Assessment methodology	Weight	High	Medium	Low
Expected pace of demand growth	Annual average demand growth rates in climate-driven scenarios vis-à-vis historical growth rates	10%	Expected pace of growth between 2023 and 2030 in the APS is over 2 times higher than historical growth rates	Expected pace of growth between 2023 and 2030 in the APS is more than 20% higher than historical growth rates	Expected pace of growth between 2023 and 2030 in the APS is similar or lower than historical growth rates
Short-term market balances	Balances between expected supply (base case) and primary supply requirements in 2026	20%	Expected supply (base case) falls short of STEPS primary supply requirements in 2026	Expected supply (base case) able to meet STEPS primary supply requirements in 2026, but falls short of APS needs	Expected supply (base case) is higher than APS primary supply requirements in 2026
Long-term market balances in climate-driven scenarios	Balances between expected supply and primary supply requirements in 2040	30%	Expected supply (base case) meets less than 60% of APS primary supply requirements in 2040	Expected supply (base case) meets 60-80% of the APS primary supply requirements in 2040.	Expected supply (base case) meets over 80% of the APS primary supply requirements in 2040.
Observed price volatility	Historical monthly price volatility between 2011 and 2023	20%	Standard deviation of indexed historical monthly prices above 35	Standard deviation of historical monthly prices between 25 and 35 (range of oil and gas)	Standard deviation of historical monthly prices below 25
Impact on clean energy cost	Share of a material in total cost of end-use technologies	20%	Price spikes could hamper the deployment of final technologies	Modest impact on final clean energy cost	Limited impact on final clean energy cost

Geopolitical risks	Assessment methodology	Weight	High	Medium	Low
Geographical concentration of mined supply	Expected share of top 3 producing mining countries in 2030	20%	Projected top 3 country share remains above 80% in 2030 or top 1 country controls more than two thirds of global	Projected top 3 country share between 65% and 80% in 2030 or top 1 country controls more than 50% of global supply	Projected top 3 country share remains below 65% and top 1 country controls less than 50% of global supply
Geographical concentration of refined supply	Expected share of top 3 producing refining countries in 2030	30%	Projected top 3 country share remains above 80% in 2030 or top 1 country controls more than two thirds of global	Projected top 3 country share between 65% and 80% in 2030 or top 1 country controls more than 50% of global supply	Projected top 3 country share remains below 65% and top 1 country controls less than 50% of global supply
N-1 supply and demand balances	Share of N-1 supply in N-1 material requirements in 2030 (refined product basis)	15%	N-1 supply serves less than 35% of N-1 requirements in 2030 in the APS	N-1 supply serves between 35% and 60% of N-1 requirements in 2030 in the APS	N-1 supply serves over 60% of N-1 requirements in 2030 in the APS
Export risks of major suppliers	Weighted average export restriction risk score of today's production portfolio both for mining and refining	15%	Weighted average country risk score above 4	Weighted average country risk score between 2.5 and 4	Weighted average country risk score below 2.5
Hurdles to develop new projects in diversified regions	Difficulties in building supply chains in geographically diverse regions (qualitative)	20%	New capacities involve considerably higher capital and operating costs (than incumbent players) and long lead time	Building new capacities needs to overcome modest capital, lead time and technological barriers	Manageable capital, lead time and technological barriers.

Barriers to respond to disruption	Assessment methodology	Weight			
Visible stock levels	Visible stock levels in major exchanges	25%	Limited visibility in stock levels	Possible to monitor visible stock levels in major exchanges, but volumes are low compared to historical average.	Ample visible stock in major exchanges
Transparency of pricing schemes	Qualitative assessment of market liquidity and transparency of pricing schemes	25%	Price reporting driven through survey pricing and unregulated platforms with limited liquidity	Early stage regulated market trading but with limited liquidity	Established regulated market trading with ample liquidity
Availability of options to moderate demand	Availability of demand-side and technology switching options to moderate demand growth in case of supply tightness (qualitative)	25%	Limited opportunities to reduce demand without sacrificing performance	Scope for technology switching and behavioural change to reduce demand, but requires substantial time and cost commitment	Viable opportunities to reduce demand in a short period of time
Status of secondary supply	Share of secondary supply in total supply and potential for growth	25%	Share of secondary supply remains low and is not improving significantly	Share of secondary supply remains low but is improving or share remains high but with limited improvement	Share of secondary supply remains high and is improving

Exposure to ESG and climate risks	Assessment methodology	Weight	High	Medium	Low
Environmental performance: mining	Weighted average enviromental performance score of today's mined production	30%	Weighted average environmental performance score below 40	Weighted average environmental performance score between 40 and 65	Weighted average environmental performance score above 65
Environmental performance: refining	Weighted average grid carbon intensity of today's refined production	30%	Weighted average grid carbon intensity above 460 gCO2/kWh (world average)	Weighted average grid carbon intensity between 460 gCO2/kWh and 380 gCO2/kWh	Weighted average grid carbon intensity below 380 gCO2/kWh (advanced economy average)
Social and governance performance	Weighted average corruption, human rights and conflict score of today's mined production (based on V-Dem)	20%	Weighted average social and governance score below 0.33	Weighted average social and governance score between 0.33 and 0.66	Weighted average social and governance score above 0.66
Exposure to natural hazards and climate risks - water stress	Share of mines exposed to water stress risks	10%	Share of mine production located in high, extreme high and arid areas equal or above 50%	Share of mine production located in high, extreme high and arid areas between 25% and 50%	Share of mine production located in high, extreme high and arid areas below 25%
Exposure to natural hazards and climate risks - earthquake	Share of mines exposed to earthquake risks	10%	Share of mine production located in high and very high earthquake risk areas equal or above 50%	Share of mine production located in high and very high earthquake risk areas between 25% and 50%	Share of mine production located in high and very high earthquake risk areas below 25%

Key projection results

Copper demand

	Historical		Stated Policies			Announced Pledges			Net Zero by 2050		
Unit: kt Cu	**2021**	**2023**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Clean energy	5 380	6 311	10 314	12 188	12 972	12 001	16 343	17 466	14 842	19 636	19 416
Electricity networks	4 030	4 171	5 922	6 305	6 124	6 632	8 327	8 158	7 816	10 632	9 471
Electric vehicles	166	396	1 645	3 131	3 470	1 870	4 297	4 804	2 612	4 642	5 124
Solar PV	694	1 208	1 691	1 684	1 959	2 117	2 049	2 401	2 564	2 245	2 390
Other	490	536	1 055	1 068	1 419	1 382	1 670	2 103	1 850	2 116	2 430
Other uses	19 548	19 543	20 341	21 997	24 671	19 127	20 036	22 046	18 399	19 434	21 473
Total demand	24 928	25 855	30 655	34 185	37 643	31 128	36 379	39 512	33 241	39 069	40 889
Share of clean energy	22%	24%	34%	36%	34%	39%	45%	44%	45%	50%	47%

Notes: Demand is based on refined copper and excludes direct use of scrap. Electric vehicles demand includes both EV batteries and EV motors demand.

Copper supply

Unit: kt Cu	Mining					Refining			
	Historical		Base case			Historical		Base case	
	2021	2023	2030	2040		2021	2023	2030	2040
Chile	5 660	5 311	5 211	4 053	**China**	10 383	11 547	14 788	14 788
DRC	2 014	2 678	3 183	2 145	**DRC**	1 562	1 978	2 235	1 381
Peru	2 282	2 644	2 377	1 067	**Chile**	2 270	2 058	1 719	1 321
China	1 828	1 865	2 128	1 856	**Japan**	1 514	1 499	1 614	1 614
Russia	862	960	1 215	1 019	**India**	497	549	1 060	1 060
Indonesia	753	863	948	861	**-**				
Rest of world	8 026	8 187	7 350	3 888	**Rest of world**	8 747	8 706	10 506	9 781
World	21 426	22 508	22 412	14 889	**World**	24 973	26 336	31 922	29 944
Top 3 share	46%	47%	48%	54%	**Top 3 share**	57%	59%	59%	59%

Note: DRC = Democratic Republic of the Congo.

Lithium demand

	Historical		Stated Policies			Announced Pledges			Net Zero by 2050		
Unit: kt Li	2021	2023	2030	2040	2050	2030	2040	2050	2030	2040	2050
Clean energy	38	92	381	868	1041	442	1 203	1 452	616	1 308	1 573
Electric vehicles	35	83	347	808	964	398	1 124	1 353	560	1 206	1 447
Battery storage	2	9	35	59	77	44	79	99	56	102	126
Other uses	63	73	90	123	155	90	123	155	90	123	155
Total demand	101	165	471	991	1196	531	1 326	1 607	705	1 431	1 728
Share of clean energy	37%	56%	81%	88%	87%	83%	91%	90%	87%	91%	91%

Lithium supply

Unit: kt Li	Raw materials				Chemicals	Chemicals			
	Historical		Base case			Historical		Base case	
	2021	2023	2030	2040		2021	2023	2030	2040
Australia	50	84	146	128	**China**	70	114	213	215
China	17	34	103	103	**Chile**	25	46	56	56
Chile	28	46	56	56	**Argentina**	7	9	47	40
Argentina	6	9	47	40	**Australia**	0	6	30	30
Zimbabwe	2	9	34	34	**US**	0	1	17	18
Canada	0	3	20	20	**Korea**	0	0	4	5
Rest of world	4	8	44	28	**Rest of world**	0	0	6	6
World	107	194	450	408	**World**	102	176	373	370
Top 3 share	89%	85%	68%	70%	**Top 3 share**	100%	96%	85%	84%

Note: Raw materials cover extraction of lithium from hard rock ore, as well as from clays and brines. Lithium chemicals cover the first production of lithium carbonate, hydroxide, sulphates and chlorides, and excludes reprocessing.

Nickel demand

	Historical		Stated Policies			Announced Pledges			Net Zero by 2050		
Unit: kt Ni	**2021**	**2023**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Clean energy	240	478	1 585	2 411	2 074	1 953	3 381	3 132	2 794	3 584	3 094
Electric vehicles	148	299	1 184	2 081	1 799	1 338	2 862	2 508	1 825	2 921	2 634
Battery storage	7	12	18	0	0	22	0	0	28	0	0
Other	85	166	383	329	274	593	518	624	940	662	460
Other uses	2 519	2 627	2 866	3 120	3 354	2 802	2 857	3 014	2 776	2 802	2 935
Total demand	2 759	3 104	4 451	5 531	5 428	4 754	6 238	6 146	5 570	6 386	6 030
Share of clean energy	9%	15%	36%	44%	38%	41%	54%	51%	50%	56%	51%

Nickel supply

	Mining				Refining				
	Historical		Base case			Historical		Base case	
Unit: kt Ni	2021	2023	2030	2040		2021	2023	2030	2040
Indonesia	1 005	1 787	2 671	3 278	**Indonesia**	869	1 414	2 028	2 365
Philippines	390	391	345	157	**China**	882	1 065	965	964
New Caledonia	168	210	247	201	**Japan**	192	204	264	230
Russia	205	194	215	191	**Russia**	120	158	165	165
Canada	175	194	156	97	**Finland**	65	138	207	207
China	109	114	143	126	**Canada**	107	136	157	147
Australia	158	111	87	67	**Australia**	105	132	213	213
Rest of world	438	450	441	322	**Rest of world**	589	550	591	577
World	2 649	3 451	4 304	4 439	**World**	2 929	3 796	4 590	4 867
Top 3 share	60%	69%	76%	83%	**Top 3 share**	66%	71%	71%	73%

Note: Nickel refining includes nickel that is processed into either a metal, oxide, nickel pig iron, ferronickel, or sulphate and excludes outputs from intermediate production steps.

Cobalt demand

	Historical		Stated Policies			Announced Pledges			Net Zero by 2050		
Unit: kt Co	**2021**	**2023**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Clean energy	36	64	155	187	216	177	260	303	243	279	323
Electric vehicles	34	62	151	187	216	171	260	303	236	279	323
Battery storage	2	3	4	0	0	5	0	0	7	0	0
Other uses	145	150	169	198	222	167	194	218	167	193	217
Total demand	181	215	324	385	438	344	454	521	410	472	539
Share of clean energy	20%	30%	48%	49%	49%	51%	57%	58%	59%	59%	60%

Cobalt supply

	Mining					Refining			
	Historical		Base case			Historical		Base case	
Unit: kt Co	2021	2023	2030	2040		2021	2023	2030	2040
DRC	121	157	215	135	China	130	172	231	228
Indonesia	3	20	50	47	Finland	14	19	20	20
Russia	6	8	8	8	Japan	5	6	13	12
China	7	7	8	7	Indonesia	0	0	9	9
Australia	8	8	6	5	Canada	7	7	8	3
Philippines	5	6	3	3	Korea	2	3	5	5
Rest of world	30	36	36	20	Rest of world	18	18	28	28
World	179	240	326	225	World	176	224	313	305
Top 3 share	75%	77%	84%	84%	Top 3 share	86%	88%	84%	85%

Graphite demand

	Historical		Stated Policies			Announced Pledges			Net Zero by 2050		
Unit: kt	**2021**	**2023**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Clean energy	532	1 292	5 179	7 053	4 839	6 013	9 839	6 777	8 407	11 222	7 879
Electric vehicles	495	1 147	4 671	6 148	3 707	5 375	8 629	5 318	7 592	9 668	6 012
Battery storage	37	145	508	904	1 133	638	1 210	1 459	815	1 555	1 867
Other uses	3 388	3 340	4 430	6 047	7 648	4 406	6 185	7 955	4 616	6 650	8 473
Total demand	3 920	4 632	9 609	13 100	12 487	10 419	16 023	14 733	13 023	17 873	16 352
Share of clean energy	14%	28%	54%	54%	39%	58%	61%	46%	65%	63%	48%

Note: Demand is for raw natural flake graphite and synthetic graphite.

Graphite supply

Unit: kt	Mining (natural graphite)					Refined battery-grade supply			
	Historical		Base case			Historical		Base case	
	2021	2023	2030	2040		2021	2023	2030	2040
China	1 140	1 320	1 905	2 160	**China**	701	1 852	5 125	6 892
Mozambique	77	97	239	339	**Japan**	121	124	97	123
Madagascar	82	66	269	223	**United States**	12	16	69	123
Russia	28	29	34	51	**Canada**	0	0	31	80
Tanzania	0	0	33	39	**Sweden**	0	0	35	56
Canada	11	5	25	25	**Finland**	0	0	26	54
Rest of world	116	100	237	215	**Rest of world**	41	45	99	153
World	1 455	1 617	2 742	3 052	**World**	875	2 037	5 481	7 481
Top 3 share	89%	92%	88%	89%	**Top 3 share**	97%	98%	97%	95%

Note: Refined battery-grade supply includes spherical graphite made from natural flake graphite and synthetic anode production.

Rare earth elements demand

	Historical		Stated Policies			Announced Pledges			Net Zero by 2050		
Unit: kt REE	**2021**	**2023**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Clean energy	11	16	40	48	57	46	64	78	62	72	80
Electric vehicles	3	7	23	36	40	25	46	51	33	48	52
Wind	8	10	17	12	17	22	19	27	29	24	28
Other uses	67	76	87	105	123	87	105	123	86	104	123
Total demand	78	93	127	153	180	134	169	200	148	176	202
Share of clean energy	14%	18%	31%	32%	32%	35%	38%	39%	42%	41%	39%

Note: Rare earth elements refer only to four magnet rare earths, neodymium, praseodymium, dysprosium and terbium.

Rare earth elements supply

	Mining				Refining				
	Historical		Base case			Historical		Base case	
Unit: kt REE	2021	2023	2030	2040		2021	2023	2030	2040
China	32	47	58	62	**China**	53	70	81	86
Australia	4	5	19	20	**Malaysia**	4	4	13	13
Myanmar	6	11	10	10	**United States**	0	0	4	4
United States	6	6	7	7	**Australia**	0	0	4	4
Rest of world	6	6	13	14	**Rest of world**	2	2	5	5
World	55	75	107	114	**World**	59	76	106	110
Top 3 share	81%	85%	81%	81%	**Top 3 share**	98%	98%	92%	93%

Note: Rare earth elements refer only to four magnet rare earths, neodymium, praseodymium, dysprosium and terbium.

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Abbreviations and acronyms

ACSR	aluminium conductor steel reinforced
ADMC	African Minerals Development Centre
APS	Announced Pledges Scenario
ASM	artisanal and small-scale mining
ASSB	all solid-state battery
BEV	battery electric vehicle
BTM	behind-the-metre
CAD	Canadian dollar
CATL	Contemporary Amperex Technology Co., Limited
CBAM	Carbon Border Adjustment Mechanism
CEEPI	Clean Energy Equipment Price Index
CME	Chicago Mercantile Exchange
CMETC	Critical Mineral Exploration Tax Credit
CMOC	CMOC Group Limited
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
COP28	28th Conference of the Parties to the United Nations Framework Convention on Climate Change
CRMA	Critical Raw Materials Act
CSDDD	Corporate Sustainability Due Diligence Directive
CSRD	Corporate Sustainability Reporting Directive
CTP	cell-to-pack
DFC	International Development Finance Corporation
DFI	development finance institutions
DLA	Defense Logistics Agency
DoD	Department of Defense
DOE	Department of Energy
DRC	Democratic Republic of the Congo
DSTP	deep-sea tailings placement
EAF	electric arc furnace
EBIT	earnings before interest and taxes
ECA	export credit/insurance agencies
EGC	Enterprise Générale du Cobalt
EITI	Extractive Industries Transparency Initiative
EMDE	emerging market and developing economies
EREV	extended-range electric vehicle
ESG	environmental, social and governance
EU	European Union
EUR	euro
EV	electric vehicle
G7	Group of Seven intergovernmental forum
GEC Model	Global Climate and Energy Model
GHG	greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
GISTM	Global Industry Standard on Tailings Management
GM	General Motors
HALEU	high-assay low-enriched uranium
HDPE	high-density polyethylene
HMS	heavy mineral sand
HPAL	high-pressure acid leaching
HPMS	Hydrogen Processing of Magnet Scrap
HREE	heavy rare earth elements
HVDC	high-voltage direct current

IAC ionic adsorption clay
IAD ionic adsorption deposit
ICE internal combustion engine
ICMM International Council on Mining and Materials
IEA International Energy Agency
IOSCO International Organization of Securities Commissions
IPCC Intergovernmental Panel on Climate Change
IRA Inflation Reduction Act
IRMA Initiative for Responsible Mining Assurance
KEXIM Korea Export-Import Bank
KFM Kisanfu copper-cobalt mine
KIO Kachin Independence Organisation
Korea Republic of Korea
LAC Latin America
LCE lithium carbonate equivalent
LDV light-duty vehicle
LFP lithium iron phosphate
LIBS laser-induced breakdown
LME London Metal Exchange
LMFP lithium manganese iron phosphate
LMR-NMC lithium-manganese-rich NMC
LNMO lithium nickel manganese oxide
LPO Loan Programs Office
LREE light rare earth elements
M&A mergers and acquisitions
MAC Mining Association of Canada
METC Mineral Exploration Tax Credit
MHP mixed-hydroxide precipitate
MIDA Malaysian Investment Development Authority
MoU memorandum of understanding
MSP Minerals Security Partnership
Na-ion Sodium-ion
NCA nickel cobalt aluminium
NDC Nationally Determined Contributions
NdFeB neodymium iron boron
NMC nickel manganese cobalt
NPI nickel pig iron
NZE Net Zero Emissions By 2050 Scenario
OECD Organisation For Economic Co-operation and Development
OEM original equipment manufacturer
OSBF oxygen-rich side blowing furnace
OTC over-the-counter
PAL pressure acid leaching
PEM proton exchange membrane
PEX polyethylene
PGMs platinum group metals
PHEV plug-in hybrid electric vehicles
PIA Promotion of Investment Act
PV photovoltaic
PRA price reporting agency
R&D research and development
REE rare earth elements
REO rare earth oxides
RKEF rotary kiln electric furnace
SGPI General Secretariat for Investment
SHFE Shanghai Futures Exchange
SIF Strategic Innovation Fund

Si-Gr silicon-doped graphite
STEPS Stated Policies Scenario
SUV sport utility vehicle
SWF sovereign wealth fund
SxEw solvent extraction and electrowinning
TC/RC spot treatment and refining charge
TFM Tenke Fungurume mine
U-235 uranium-235
UK United Kingdom
UNFC United Nation's Framework Classification for Resources
US United States
USD United States dollar
VC venture capital
XRF X-ray Fluorescence

Units of measure

bps basis points
g CO_2 grammes of carbon dioxide
GW gigawatt
GWh gigawatt-hour
kg kilogramme
km kilometre
km^2 square kilometre
kt kilotonne
Mt million tonnes
Mtpa million tonnes per annum
MW megawatt
TWh terawatt-hours

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