Global Critical Minerals Outlook 2025

INTERNATIONAL ENERGY AGENCY

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Revised version, June 2025
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Abstract

Critical minerals, which are essential for a range of energy technologies and for the broader economy, have become a major focus in global policy and trade discussions. Price volatility, supply chain bottlenecks and geopolitical concerns make the regular monitoring of their supply and demand extremely vital.

The *Global Critical Minerals Outlook* 2025 includes a detailed assessment of the latest market and investment trends, along with their implications for critical minerals security. As in last year's *Outlook*, it provides a snapshot of recent industry developments from 2024 and early 2025 and offers medium- and long-term projections for the supply and demand of key energy minerals, taking into account the latest policy and technology developments.

The 2025 *Outlook* also explores key techno-economic issues such as policy mechanisms to support diversification; mineral supply chains for emerging battery technologies; recent innovations in mining, refining and recycling; and a broader view on strategic minerals for applications beyond the energy sector. As a new chapter, the report also includes a comprehensive review of mineral markets and policy developments in different regions. The report will be accompanied by an updated version of our Critical Minerals Data Explorer, an interactive online tool that allows users to explore the latest IEA projections.

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Executive summary

Demand for key energy minerals continued to grow strongly in 2024. Lithium demand rose by nearly 30%, significantly exceeding the 10% annual growth rate seen in the 2010s. Demand for nickel, cobalt, graphite and rare earths increased by 6-8% in 2024. This growth was largely driven by energy applications such as electric vehicles, battery storage, renewables and grid networks. In the case of copper, the rapid expansion of grid investments in China has been the single largest contributor to demand growth over the past two years. For battery metals such as lithium, nickel, cobalt and graphite, the energy sector accounted for 85% of total demand growth over the same period.

Despite this rapid demand growth, major supply increases – led by China, Indonesia and the Democratic Republic of the Congo – exerted downward pressure on prices, especially for battery metals. The swift increase in battery metal production highlighted the sector's ability to scale up new supply more quickly than for traditional metals like copper and zinc. Since 2020, supply growth for battery metals has been twice the rate seen in the late 2010s. As a result, following the sharp price surges of 2021 and 2022, prices for key energy minerals have continued to decline, returning to pre-pandemic levels. Lithium prices, which had surged eightfold during 2021-22, fell by over 80% since 2023. Graphite, cobalt and nickel prices also dropped by 10 to 20% in 2024.

Despite strong expectations for future demand growth, investment decisions today face significant market and economic uncertainties. Investment momentum in critical mineral development weakened in 2024, with spending rising by just 5%, down from 14% in 2023. Adjusted for cost inflation, real investment growth was just 2%. Exploration activity plateaued in 2024, marking a pause in the upward trend seen since 2020. While exploration spending continued to rise for lithium, uranium and copper, it declined notably for nickel, cobalt and zinc. Start-up funding is also showing signs of a slowdown. Today's low mineral prices are not providing the signal to invest, and projects involving new entrants have been most affected by the uncertainty.

Diversification is the watchword for energy security, but the critical minerals world has moved in the opposite direction in recent years, particularly in refining and processing. Between 2020 and 2024, growth in refined material production was heavily concentrated among the leading suppliers. As a result, the geographic concentration of refining has increased across nearly all critical minerals, particularly for nickel and cobalt. The average market share of the top three refining nations of key energy minerals rose from around 82% in 2020 to 86% in 2024 as some 90% of supply growth came from the top single supplier alone: Indonesia for nickel and China for cobalt, graphite and rare earths.

Our detailed analysis of announced projects suggests that progress towards more diversified refining supply chains is set to be slow. Looking ahead to 2035, the average share of the top three refined material suppliers is projected to decline only marginally to 82%, effectively returning to the concentration levels seen in 2020. China's stronghold extends beyond refining; two-thirds of global battery recycling capacity growth since 2020 has been in China.

Mining activity shows a similar trend, though it remains somewhat less concentrated than refining. Most recent growth in mining output stemmed from established producers such as the Democratic Republic of the Congo (DRC) for cobalt, Indonesia for nickel, and China for graphite and rare earths. As a result, the average market share of the top three mining countries for key energy minerals rose from 73% in 2020 to 77% in 2024. Lithium was a notable exception, with a major portion of supply growth coming from emerging producers like Argentina and Zimbabwe. Looking ahead, some diversification is coming into view for the mining of lithium, graphite and rare earths. However, geographical concentration is expected to intensify for copper, nickel and cobalt. Overall, the share of the top three producers is projected to decline slightly to the levels seen in 2020, similar to trends observed in refining.

Projected supply-demand balances through to 2035 are improving compared with a few years ago, but major concerns remain, especially for copper. The growing number of mining and refining project announcements promises a notable increase in future production volumes. For nickel, cobalt, graphite and rare earths, expected supplies are catching up with projected demand growth under today's policy settings, if planned projects proceed on schedule. However, copper and lithium are major exceptions. Despite strong copper demand from electrification, the current mine project pipeline points to a potential 30% supply shortfall by 2035 due to declining ore grades, rising capital costs, limited resource discoveries and long lead times. For lithium, near-term markets appear well-supplied, but rapidly growing demand is expected to push the market into deficit by the 2030s; however, the prospects for developing new lithium projects are much more favourable than for copper.

Today's markets may appear well-supplied, but export restrictions and risks to security of supply are proliferating. Amid rising supply concentration, an expanding number of export control measures on critical minerals have been introduced, particularly since 2023. In December 2024, China restricted the export of gallium, germanium and antimony, key minerals for semiconductor production, to the United States. This was followed by further announcements in early 2025, including restrictions on tungsten, tellurium, bismuth, indium and molybdenum and on seven heavy rare earth elements. In February 2025, the DRC announced a four-month suspension of cobalt exports to curb falling prices. Currently, more than half of a broader group of energy-related minerals are subject to some form of export controls. These restrictions are not only increasing in number but also expanding in scope to cover not just raw and refined materials but also processing technologies, such as those for lithium and rare earth refining.

High market concentration increases vulnerability to supply shocks, particularly if, for any reason, supply from the largest producing country is disrupted. When the largest supplier and its demand is excluded, the overall market balances become starkly different. For battery metals and rare earths, supplies outside the leading producer meet on average only half of the remaining demand in 2035. This means that, even in a well-supplied market, critical mineral supply chains can be highly vulnerable to supply shocks, be they from extreme weather, a technical failure or trade disruptions.

The impact of a critical minerals supply shock can be far-reaching, bringing higher prices for consumers and reducing industrial competitiveness. A sustained supply shock for battery metals could increase global average battery pack prices by as much as 40-50%. There is already a major battery manufacturing cost gap across regions. Prolonged supply disruptions could widen cost disadvantages for other battery manufacturers vis-à-vis China, potentially hindering efforts to diversify manufacturing supply chains.

Extending our analysis to a broader range of 20 energy-related, multisectoral minerals highlights additional vulnerabilities. These minerals play a vital role across sectors such as high-tech, aerospace and advanced manufacturing. While the market sizes for these minerals are relatively small, supply disruptions can have outsized economic impacts.

Major risk areas for this broader group of strategic minerals include high supply chain concentration, price volatility and by-product dependency. China is the dominant refiner for 19 of the 20 minerals analysed, holding an average market share of around 70%. Three-quarters of these minerals have shown greater price volatility than oil, and half have been more volatile than natural gas. Around half are produced as by-products, limiting the flexibility of supply to respond to market signals. Substitution options are also limited; many minerals, such as tantalum, titanium and vanadium, have few viable alternatives without major cost or performance trade-offs.

Policy makers have woken up to these energy security challenges with a wave of new policy initiatives. Governments around the world are intensifying efforts to secure critical mineral supplies through public funding, strategic partnerships and domestic policy reforms. The United States issued a series of executive orders to expedite permitting and increase investments in domestic projects. The European Commission designated 47 strategic projects under the EU Critical Raw Materials Act to fast-track development and enhance financing access. The International Energy Agency has launched a new Critical Minerals Security Programme to address key vulnerabilities. Australia, Canada and other nations have launched major funding programmes. Meanwhile, resource-rich countries are implementing policies to retain greater economic value from their mineral resources.

Diversification will not materialise through market forces alone; well-designed policy support and partnerships are essential. Capital costs for projects in diversified regions are typically around 50% higher than for incumbent producers. These higher costs, combined with price volatility and economic uncertainty, are making it difficult to build up diversified supply. Public financing support can help to bring forward new projects, but rule-based market mechanisms are also required to support their operation. Well designed price stabilisation schemes, such as contract-for-differences and cap-and-floor models, can help smooth out price volatility and mobilise private investment without imposing excessive fiscal burdens. Volume guarantee mechanisms can also support investment by providing greater demand certainty for new projects. Standards-based market access policies are another option, enabling only minerals that meet certain sustainability or production criteria to qualify for accessing specific market segments, such as strategic reserves or public procurement channels. For instance, targeted incentives for cleaner nickel production could unlock sizeable supply volumes outside today's dominant producers and reduce global market concentration by 7% by 2035.

Global collaboration remains essential to diversifying supply sources, linking resource-rich countries with those possessing refining capabilities and downstream consumers. Major opportunities exist for cross-border partnerships and collaboration in highly concentrated supply chains. For example, African nations such as Madagascar, Mozambique and Tanzania hold around a quarter of global graphite resources, while Germany, Japan, Korea and the United States have the capacity and plans to produce graphite anode materials. Similarly, ample rare earth resources exist in Australia, Brazil, Viet Nam and others, while Europe, Malaysia and the United States are investing in separation facilities. Permanent magnet manufacturing capacities are being developed in Europe, Japan, Korea and the United States. Mapping out opportunities for connections across the whole supply chain, rather than focusing solely on a single part of the value chain, can help realise the potential of partnerships in diversifying supply sources. This needs to be followed by cooperative frameworks such as co-investment, offtake agreements, and shared de-risking mechanisms.

New technologies in mining, refining and recycling hold major potential to scale up diversified supplies. A range of emerging innovations have the potential to transform mineral production. In mining, these include AI-based exploration, direct lithium extraction, the processing of ionic adsorption clays, and the re-mining of tailings and mine waste. In refining and recycling, advances such as novel synthetic graphite production, sulphide ore leaching and advanced sorting technologies could represent promising breakthroughs. For example, innovations such as AI-based geological exploration could reduce drilling costs by up to 60% and as much as quadruple discovery success rates. Technologies that enable rare earth extraction from ionic adsorption clay deposits could significantly reduce capital intensity and waste generation, opening up new production opportunities in countries such as Australia, Brazil and

Uganda. International collaborations can also play a vital role in addressing technology bottlenecks in building diversified supplies.

Emerging battery technologies are challenging the incumbent nickel-based lithium-ion batteries, and these are not immune to high supply concentration and volume risks. Lithium iron phosphate (LFP) batteries have surged in recent years, covering nearly half of the electric car market, up from less than 10% in 2020, and emerging technologies like sodium-ion and manganese-rich lithium-ion batteries are also gaining traction. However, the supply chains for these technologies are significantly more concentrated than those for nickel-based batteries. China produces 75% of the world's purified phosphoric acid, essential for LFP batteries, and 95% of high-purity manganese sulphate, a key input for manganese-rich and sodium-ion battery chemistries. These two materials are emerging as key chokepoints, with current project pipelines indicating the potential for major supply gaps. Planned projects for purified phosphoric acid are insufficient to meet projected demand from around 2030. High purity manganese sulphate supplies from announced projects meet only 55% of expected 2035 demand under today's policy settings. Sodium-ion batteries offer some upstream diversification potential, with the United States and Europe playing active roles in soda ash, caustic soda and biomass supplies. Yet the downstream supply chain – for cells, cathodes and hard carbon anodes – remains dominated by China. Given the growing competitiveness and market share of LFP and other emerging technologies, it is becoming increasingly important for policy makers to pay close attention to supply chain vulnerabilities in these new technologies.

Sustainability reporting continues to gain traction across major producers. Around 85% of the 25 major mining companies disclosed performance across 10 key environmental and social indicators in 2023, rising from 60% in 2020. While environmental indicators such as emissions, water usage and waste have started to improve after several years of stagnation, advances in social metrics, such as worker safety, appear to be slowing. Water and climate risks present a major issue; in 2024, 7% of global copper supply was at risk of disruption due to floods or droughts, a figure that is set to rise in the future. Traceability systems can help meet various policy goals, including contributing to the development of sustainable, responsible and secure mineral supply chains.

In a world of high geopolitical tensions, critical minerals have emerged as a frontline issue in safeguarding global energy and economic security. The wave of recent export restrictions highlights the strategic urgency of strengthening the resilience and diversity of critical mineral supplies as the world moves towards a more electrified, renewables-rich energy system. Through its Critical Minerals Security Programme, the IEA is scaling up efforts to bolster mineral security by building systems to enhance resilience against potential disruptions, supporting the acceleration of project development in diverse regions, and deepening market monitoring capabilities.

Introduction

Introduction

Critical minerals markets experienced another turbulent year in 2024. While some base metal prices saw a slight increase, many continued to decline as supply growth outpaced demand. Battery metal prices remained particularly subdued, though the pace of decline was less severe than in 2023.

Security of supply is far from guaranteed even in today's relatively well-supplied markets. Growing geopolitical tensions, marked by a series of export controls on key materials and technologies, have heightened supply risks: disruptions and restrictions to flows of critical minerals are not just a theoretical concern. However, the low-price environment presents significant challenges to supply diversification efforts, disproportionately affecting prospective projects located outside the main incumbent producers. These developments underscore the continued importance of enhancing diversity and resilience in critical mineral supplies, keeping the issue firmly at the forefront of the policy agenda.

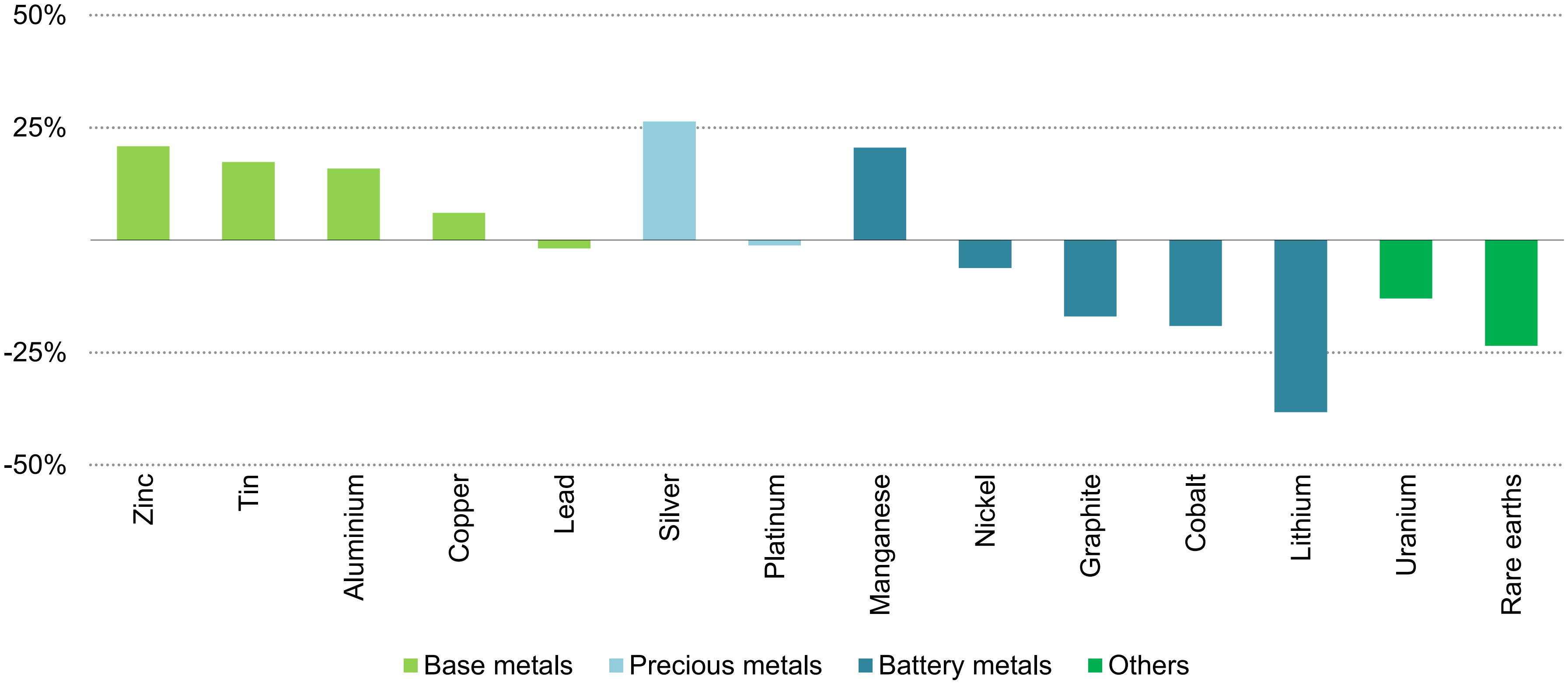
The International Energy Agency (IEA) remains committed to working with governments, industry and other stakeholders to address these emerging challenges, based on its long-standing experience in safeguarding energy security. Over the past years, the IEA has been expanding its work in this area by conducting systematic market monitoring, advancing the Voluntary Critical Minerals Security Programme, and promoting sustainable and responsible supplies.

The Global Critical Minerals Outlook is a crucial component of the IEA's efforts to support mineral security by providing a clear understanding of today's market dynamics and what they mean for the future. It analyses the latest market, technology and policy trends; reviews the future demand and supply prospects for key minerals; and assesses potential risks along the supply chain.

In addition to the usual updates on demand, supply, prices and investment needs, this year's edition goes into detail on the security risks associated with today's high concentration of supply and highlights areas requiring greater policy attention, including policy tools to incentivise supply diversification, supply-side technology innovation and supply chain risks related to emerging battery technologies. The report also examines potential risk factors for a broader set of energy-related strategic minerals.

While base metal prices saw a modest uptick, battery metal prices continued to decline in 2024 due to rapidly increasing supply volumes

Change in selected commodity prices in 2024



Notes: Change in prices between December 2023 and December 2024. Assessments based on the London Metal Exchange price index (zinc, tin, aluminium, copper, lead, platinum, nickel, cobalt and lithium), London Bullion Market Association price index (silver), China manganese sulphate 32% (manganese), China uncoated spherical graphite 99.95% (graphite) and Nuexco weekly spot price (uranium). The average of magnet rare earth elements for rare earths.

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 energy applications. The main focus is on "key energy minerals", such as copper, lithium, nickel, cobalt, graphite and rare earth elements, for which we provide detailed demand and supply projections based on bottom-up modelling. However, the report also discusses key trends for other important materials such as aluminium, manganese, phosphate, platinum-group metals, silicon, silver and uranium in Chapter 2.

Our assessment of mineral demand in the energy sector includes demand for low-emissions power generation (solar photovoltaic [PV], wind, hydro, nuclear and other renewables), electric vehicle (EV) 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 2024, updated for the latest data points on EVs from the Global EV Outlook 2025.

- The **Stated Policies Scenario (STEPS)** is an exploratory scenario that provides a sense of the prevailing direction of travel for the energy system, based on today's policy settings.
- The **Announced Pledges Scenario (APS)** assumes that governments meet, in full and on time, their national energy and climate targets, including longer-term net zero emissions targets and pledges in nationally determined contributions (NDCs).
- The **Net Zero Emissions by 2050 (NZE) Scenario** is a normative scenario that charts a pathway for the global energy sector to reach net zero carbon dioxide (CO_2) emissions by 2050. The NZE Scenario also meets the key energy-related United Nations Sustainable Development Goals (SDGs) such as universal access to reliable modern energy services and major improvements in air quality.

It should be noted that the World Energy Outlook 2025 will contain an updated set of scenarios that reflect the wide spectrum of possible outcomes that today's markets and policies imply. These will include exploratory scenarios that flow from different assumptions about existing policies, including the Current Policies Scenario, as well as normative pathways that achieve energy and emissions goals in full, including climate targets, improvements in air quality and universal access to modern energy. Once the updated scenarios become available, mineral demand and supply projections will also be updated and made available through the IEA Critical Minerals Data Explorer.

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

Mineral supply projections are based on a detailed review of all announced projects across the globe. We present 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. Neither case considers projects that are in the very early stages of development, nor includes theoretical projects for which resources might be adequate but which have not been proposed. For these reasons, our supply projections focus 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 mineral needs in each scenario.

- **Chapter 1 (Market review of 2024)** offers a snapshot of industry developments in 2024 and early 2025. It reviews major demand, production, investment and price trends for key minerals. The chapter also discusses the latest policy developments and insights based on systematic tracking of the industry's environmental, social and governance performance.
- **Chapter 2 (Outlook for key energy minerals)** provides an outlook for demand and supply of key individual minerals and related market and policy issues. The chapter provides detailed 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 (Deep dives)** presents the strategic implications of the projection results for policy and industry stakeholders seeking to promote reliable and sustainable supplies of critical minerals. The chapter discusses four major issues: i) policy mechanisms to support supply diversification; ii) supply chain issues around emerging battery technologies; iii) scope for supply-side technology innovation (mining, refining and recycling); and iv) risk assessments for a broader set of energy-related, multi-sectoral minerals used across a wide range of end-use applications.
- **Chapter 4 (Regional snapshot)** is a new addition this year, offering a concise overview of key regions' activities and policy development related to critical mineral supply chains.

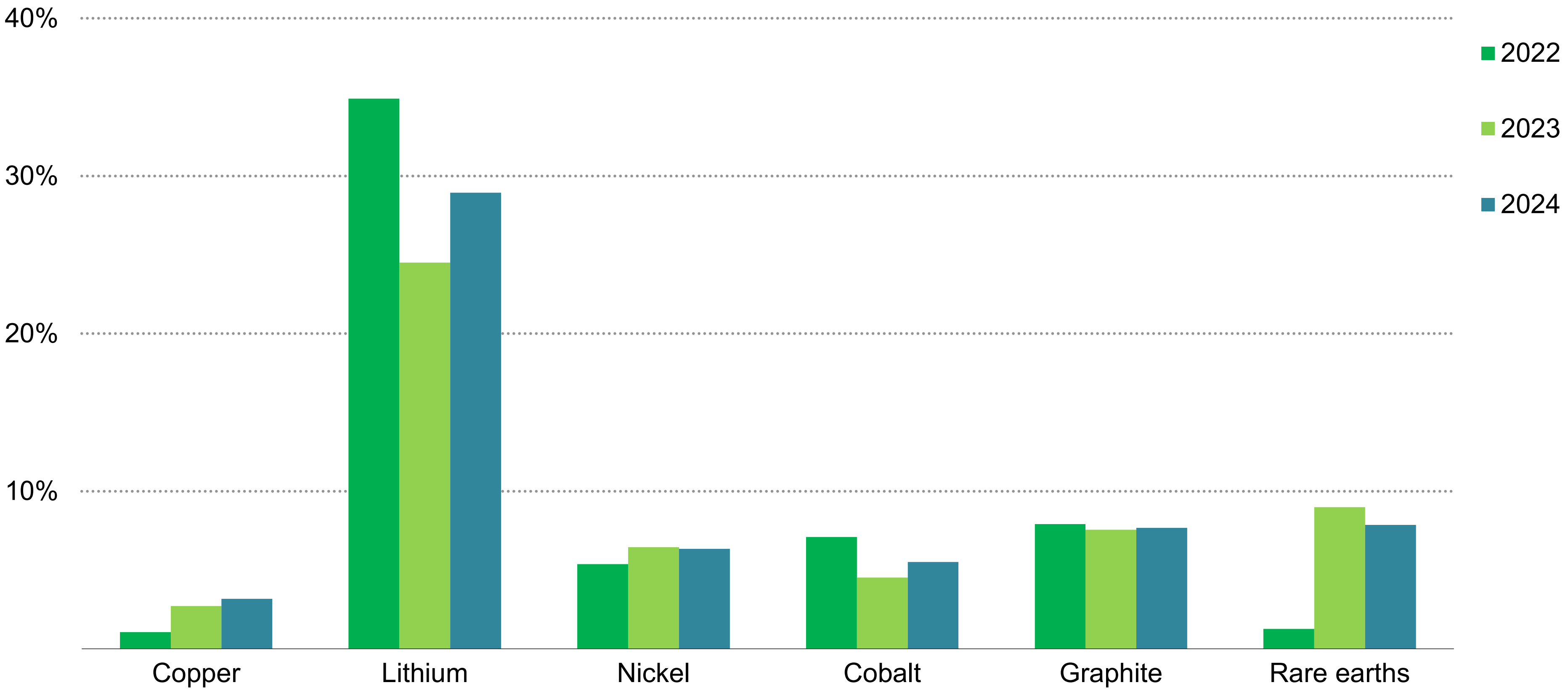
All projection results are made available in the IEA Critical Minerals Data Explorer, an interactive online tool that allows interested parties to easily access the IEA's projection data.

1. Market review of 2024

Mineral demand, production and price trends

Demand for critical minerals maintained robust growth in 2024, supported by robust energy technology deployment

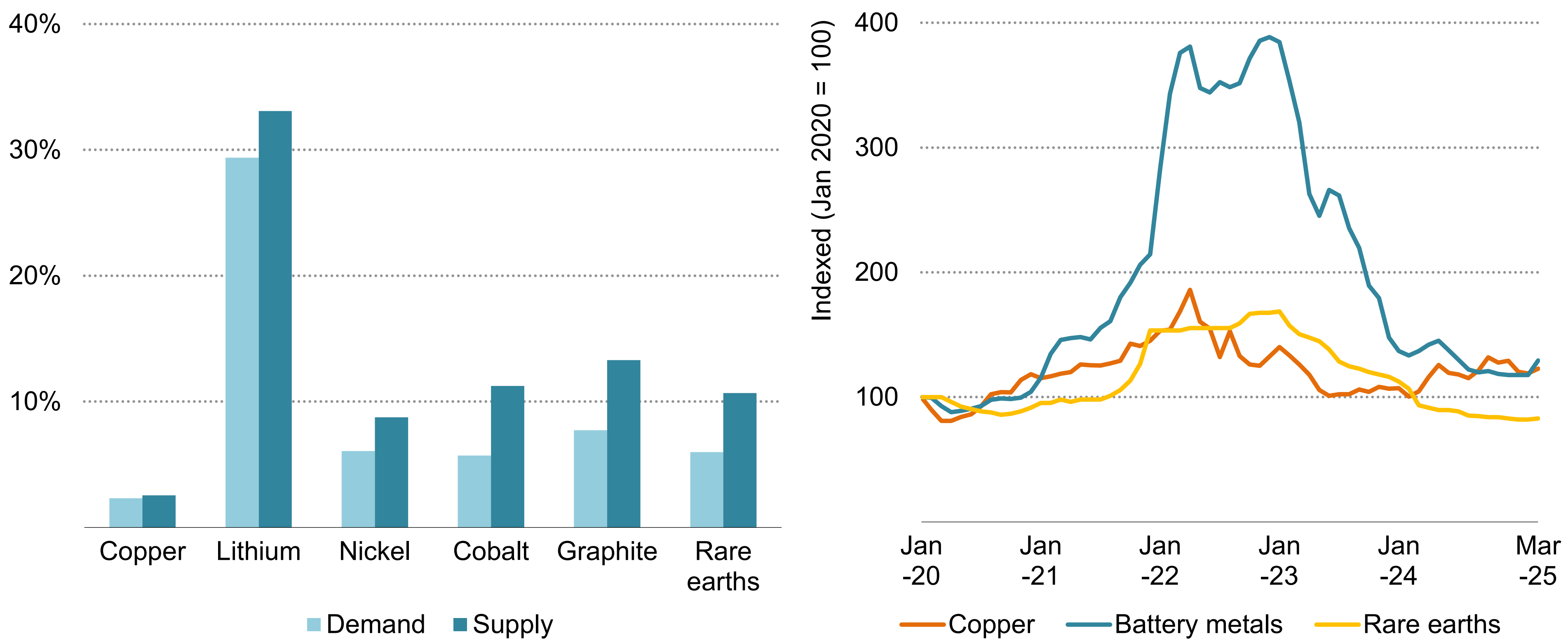
Annual change in demand for selected minerals



Note: Rare earths are magnet rare earths only.

However, supply has expanded at a faster pace than demand, resulting in downward pressure on prices, especially for battery metals

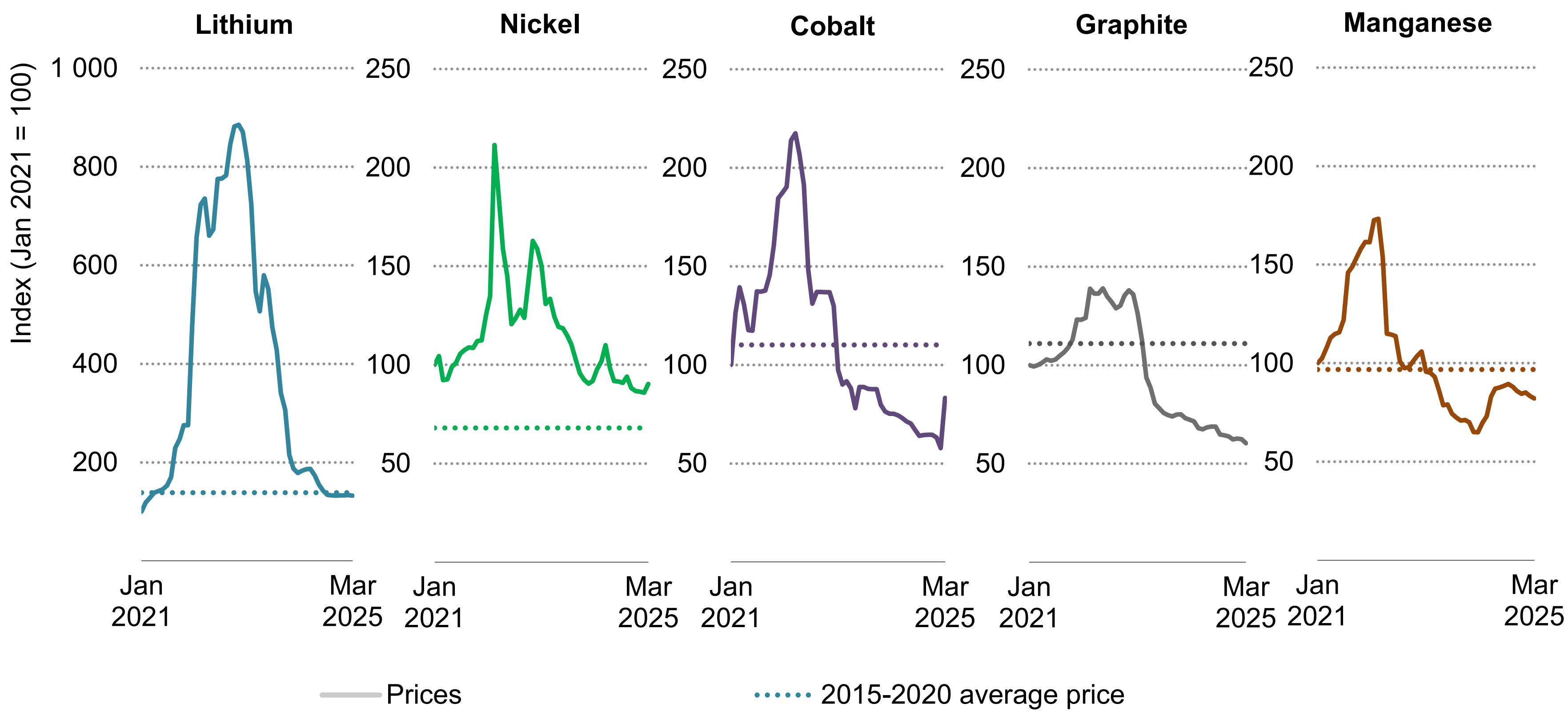
Annual average demand and supply growth between 2021 and 2024 (left), price developments (right) for selected minerals



Notes: Supply growth rates are based on refined output. Rare earths are magnet rare earths only. Battery metals include lithium, nickel, cobalt, graphite and manganese.
Sources: IEA analysis based on S&P Global and Bloomberg.

Prices for battery metals continued to decline in 2024 amid growing supply, with the exception of manganese

Price trends for selected battery metals

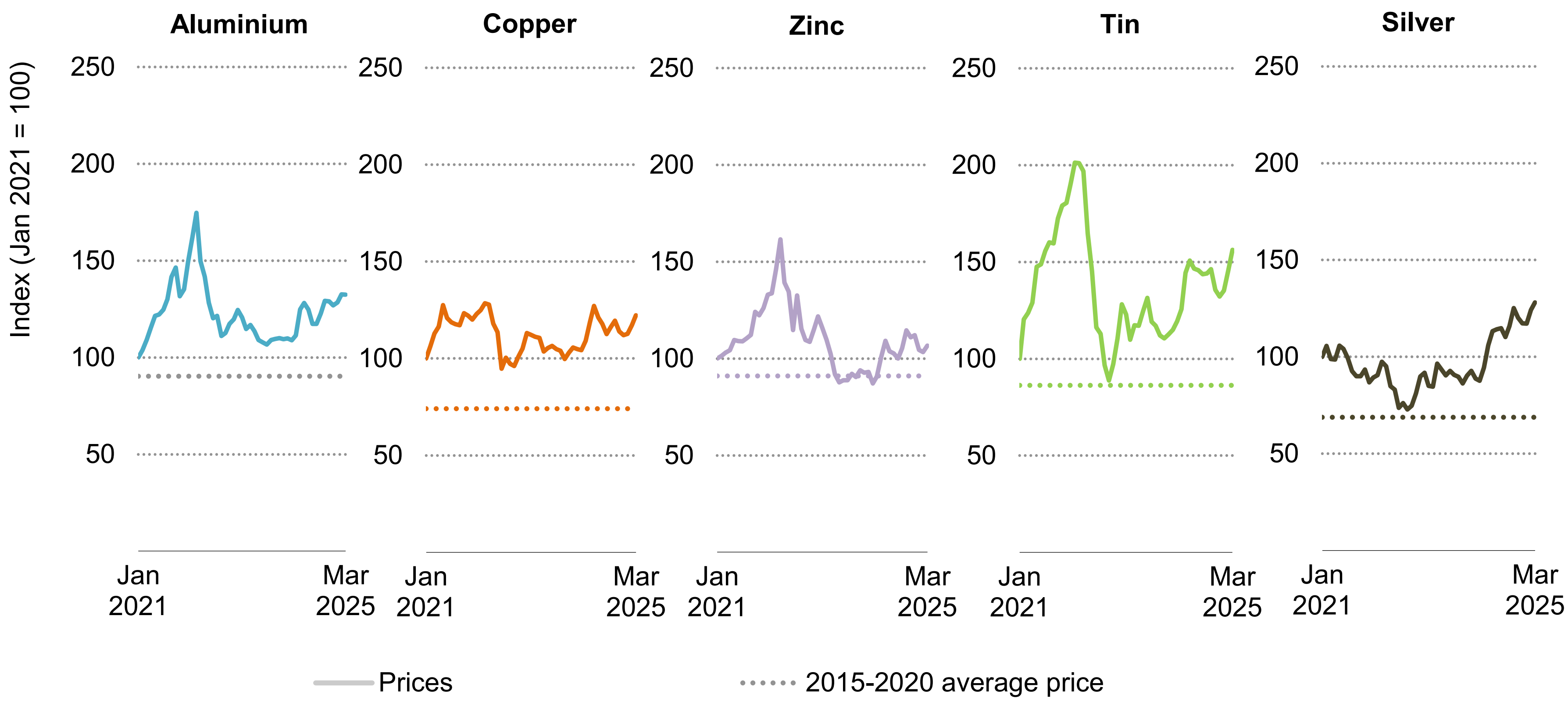


Notes: Manganese historical average from 2018-2020. Assessment based on the London Metal Exchange (LME) Lithium Carbonate Global Average, LME Nickel Cash, LME Cobalt Cash, China Spherical Graphite 99.95% and manganese sulphate 32%. Nominal prices.

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

Base and industrial metal prices saw a modest rebound in 2024 and have continued to rise in 2025, driven by improving industrial demand prospects and tightening supply dynamics

Price trends for selected base and industrial metals

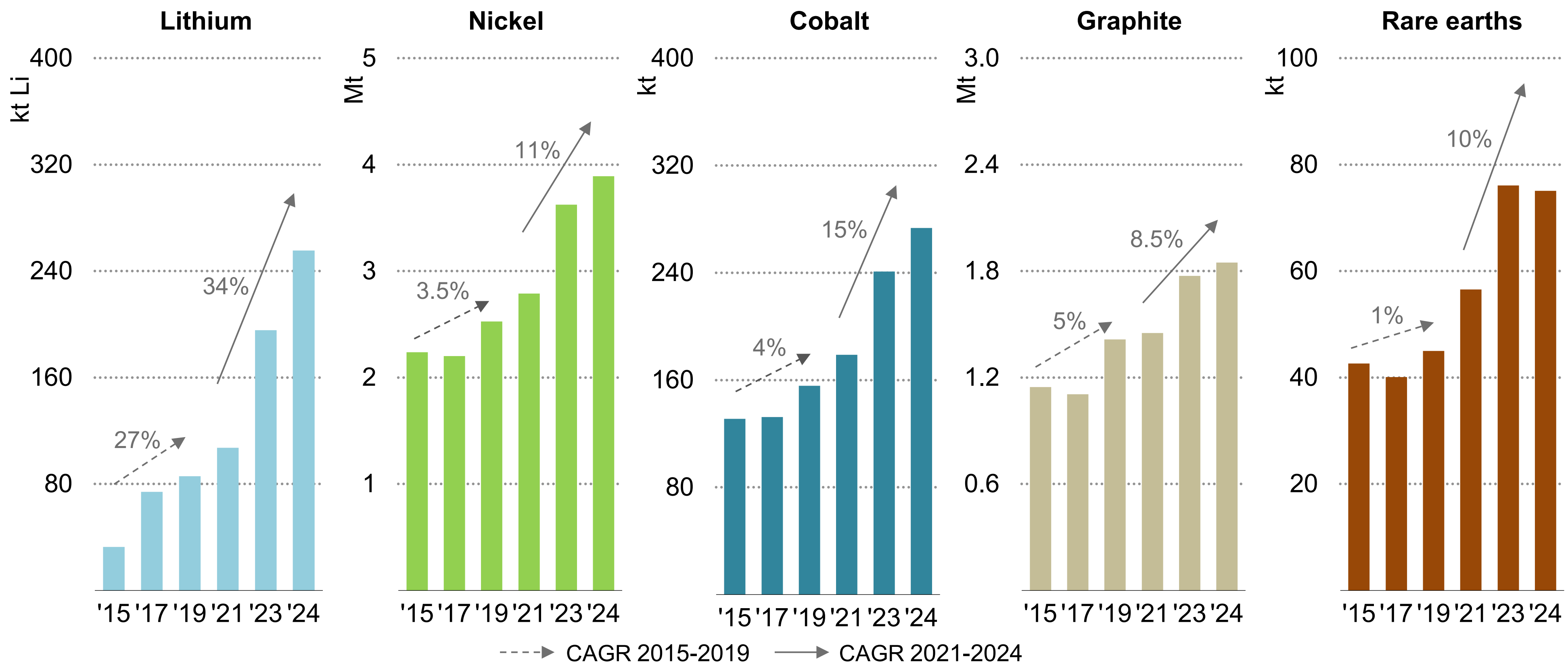


Note: Assessment based on the LME Aluminium 99.7%, LME Copper Grade A, LME special high-grade zinc 99.995%, LME-Tin 99.85% and London Bullion Market Association silver price.

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

Mined output growth for battery metals and rare earth elements has markedly accelerated in recent years…

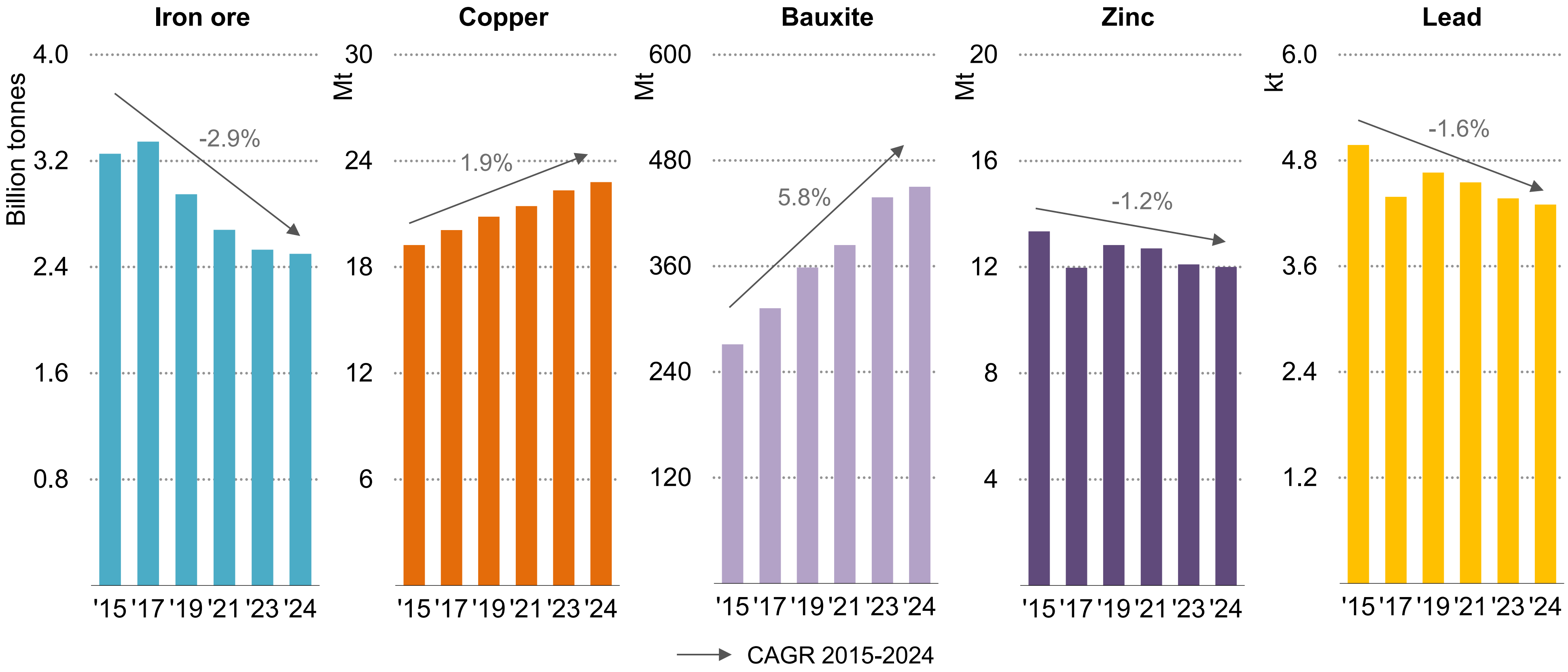
Mined production for battery metals and rare earth elements



Notes: kt = kilotonnes; Li = lithium; Mt = million tonnes; CAGR = compound annual growth rate. Graphite is for natural flake graphite. Rare earths are magnet rare earths only.

…in contrast to relatively muted growth for base metals due to long lead times, declining ore quality and permitting challenges

Mined production for selected base metals



Note: CAGR = compound annual growth rate.
Sources: IEA analysis based on USGS (2025), Mineral Commodity Summaries 2025, and S&P Global.

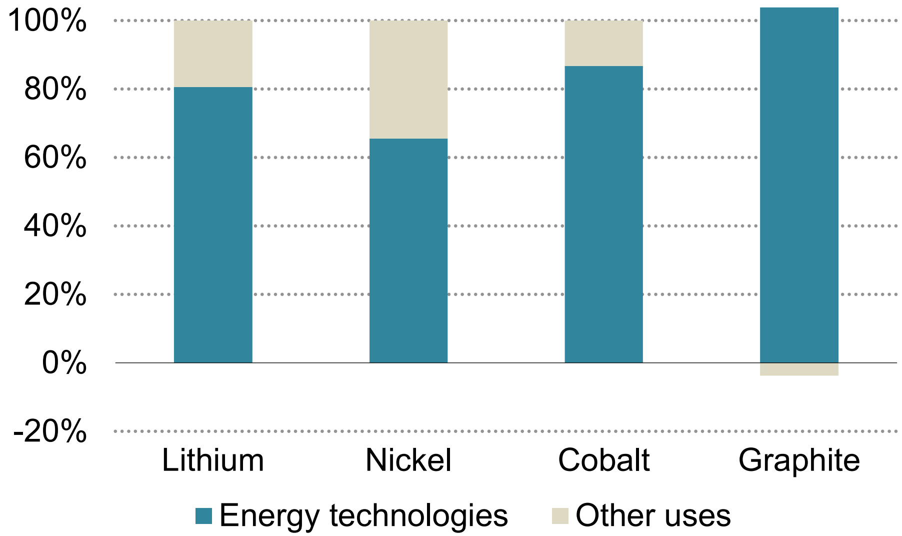
Ample supply has maintained downward pressure on prices, especially for battery metals

Demand for key energy minerals continued to grow in 2024. Lithium demand rose by nearly 30%, sustaining the strong increase seen in 2023 and significantly exceeding the 10% annual growth rate seen in the 2010s. Demand for nickel, cobalt, graphite and rare earth elements rose by 6-8% in 2024. Copper also saw robust demand growth of around 3%, outpacing the previous two years.

The growth in demand continued to be driven by energy applications such as electric vehicles (EVs), energy storage, renewables and electricity networks. For copper, the rapid expansion of grid network investment in the People's Republic of China (hereafter, "China") was the single largest factor of demand growth over the two years. Despite a slowdown in EV deployment in some markets, energy technologies continued to drive demand growth for major battery metals, contributing to some 65-90% of total demand growth over the past two years.

However, increases in supply, driven by China, Indonesia, and parts of Africa, outpaced the growth in demand. The rapid expansion of mined output for battery metals, given their relatively small supply base, demonstrated the sector's ability to bring new production online faster than traditional metals. Mining activity growth rates in the 2020s have been significantly higher than in the 2010s, driven by relatively shorter lead times and increased investments. Most of this growth over the past few years came from established producers, including the Democratic Republic of the Congo (DRC) for cobalt, Indonesia for nickel, and China for natural graphite and lithium. However, for lithium, a notable share of supply growth also came from emerging producers such as Argentina and Zimbabwe. For refined materials, production grew at a faster pace than raw material supply in many cases, supported by ample processing capacity in leading producers such as China and Indonesia.

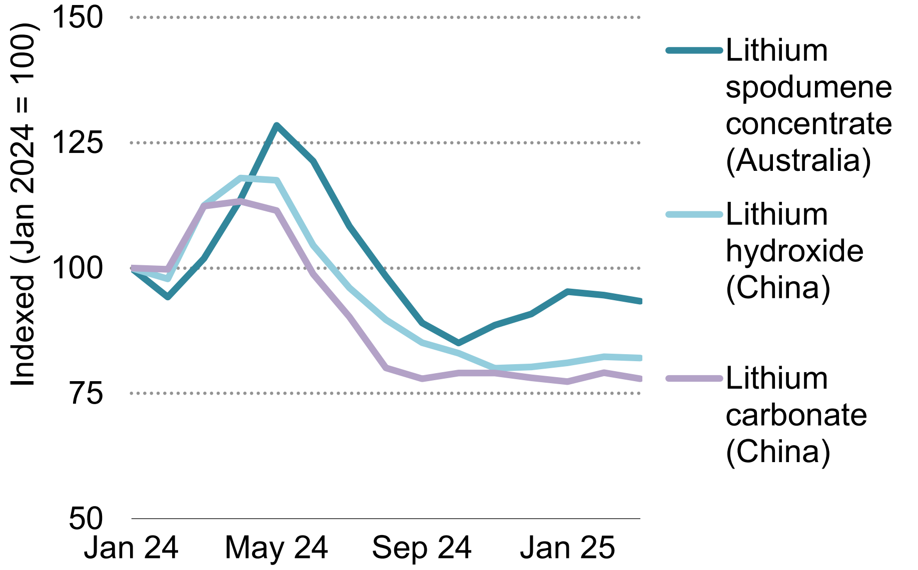
Energy sector's contribution to demand growth for selected battery metals, 2022-2024



Due to rapid production growth outpacing demand, prices for key energy minerals remained subdued in 2024. This was particularly the case for battery metals. Lithium prices have fallen by over 80% since 2023 after increasing eightfold in the previous two years. Over the course of 2024, graphite and cobalt prices fell by around 20% and nickel prices declined by 10%, though these declines were less sharp than those seen in 2023. Manganese prices stood out as an exception, rising notably in the second half of 2024 due to supply disruptions in Australia and Gabon, coupled with growing demand. As refined material supply consistently outstripped mined supply, final product prices felt more pressure than feedstocks. For example, lithium spodumene concentrate prices remained broadly stable throughout 2024 while lithium chemical prices continued to slide.

Prices for base metals such as aluminium, copper and zinc saw a rebound in 2024 and have continued to rise in 2025 due to production cuts and operational challenges in key producing regions and improving demand prospects. Expectations of economic recovery in major economies, particularly in China, supported renewed investor interest and higher prices, although the recent economic context in 2025 might affect this picture. Declining stockpiles in major exchanges signalled tighter market conditions. Overall, mined output growth for these materials was significantly slower than that of battery metals, due to declining resource quality, longer lead times, higher capital intensity and the greater complexity of developing new projects. Mining companies often prefer mergers and acquisitions over developing new greenfield projects. Tin prices surged by just under 20% in 2024 and recorded another 20% growth in the first three months of 2025 primarily due to supply disruptions in major producing countries, including Myanmar and Indonesia, as well as increased demand from the electronics and semiconductor industries. The prices spiked further in early 2025 due to the temporary closure of Bisie tin mine in the Democratic Republic of the Congo (hereafter, "DRC"). Silver prices also saw a major increase of 25% in 2024 and another 10% growth in 2025, benefiting from rising industrial demand – particularly for solar panels and electronics – alongside increased investor interest amid economic uncertainties.

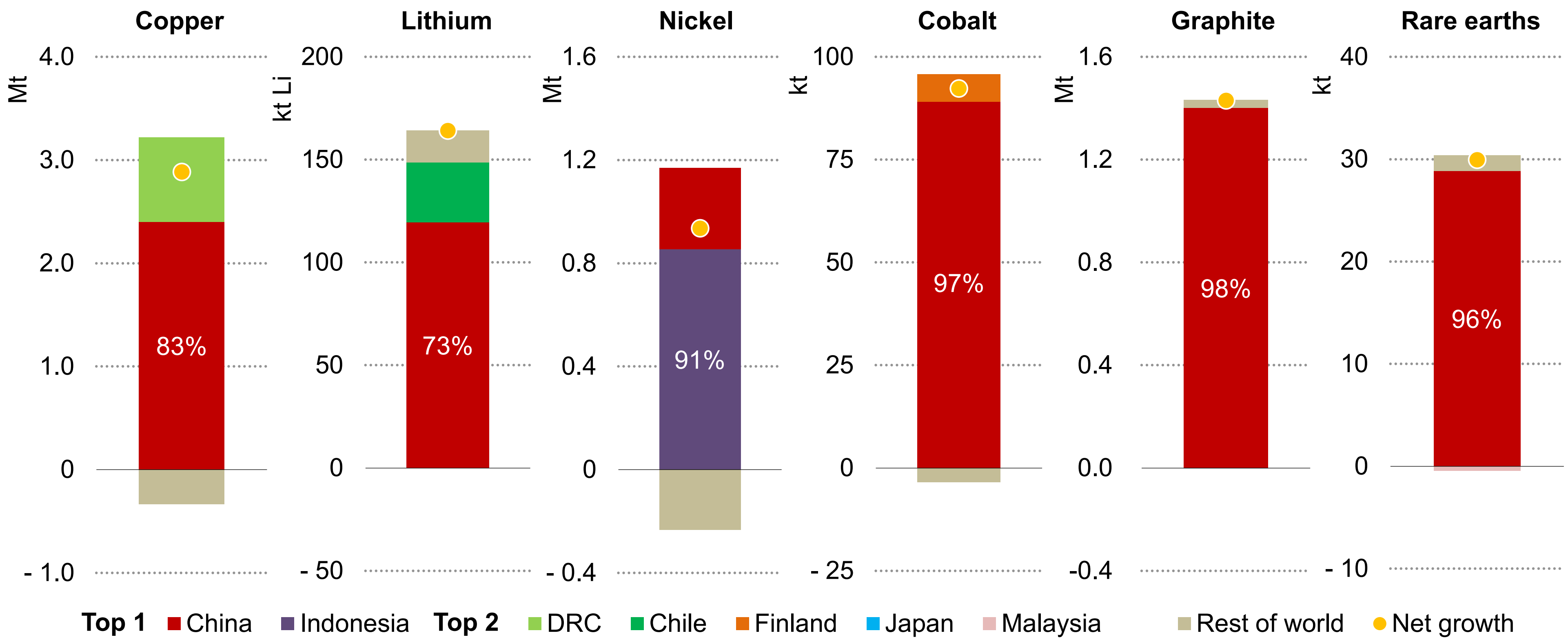
Lithium price developments in 2024



Source: IEA analysis based on S&P Global.

In recent years, growth in refined material production has been largely concentrated among the leading suppliers, driven almost entirely by the top producer in some cases

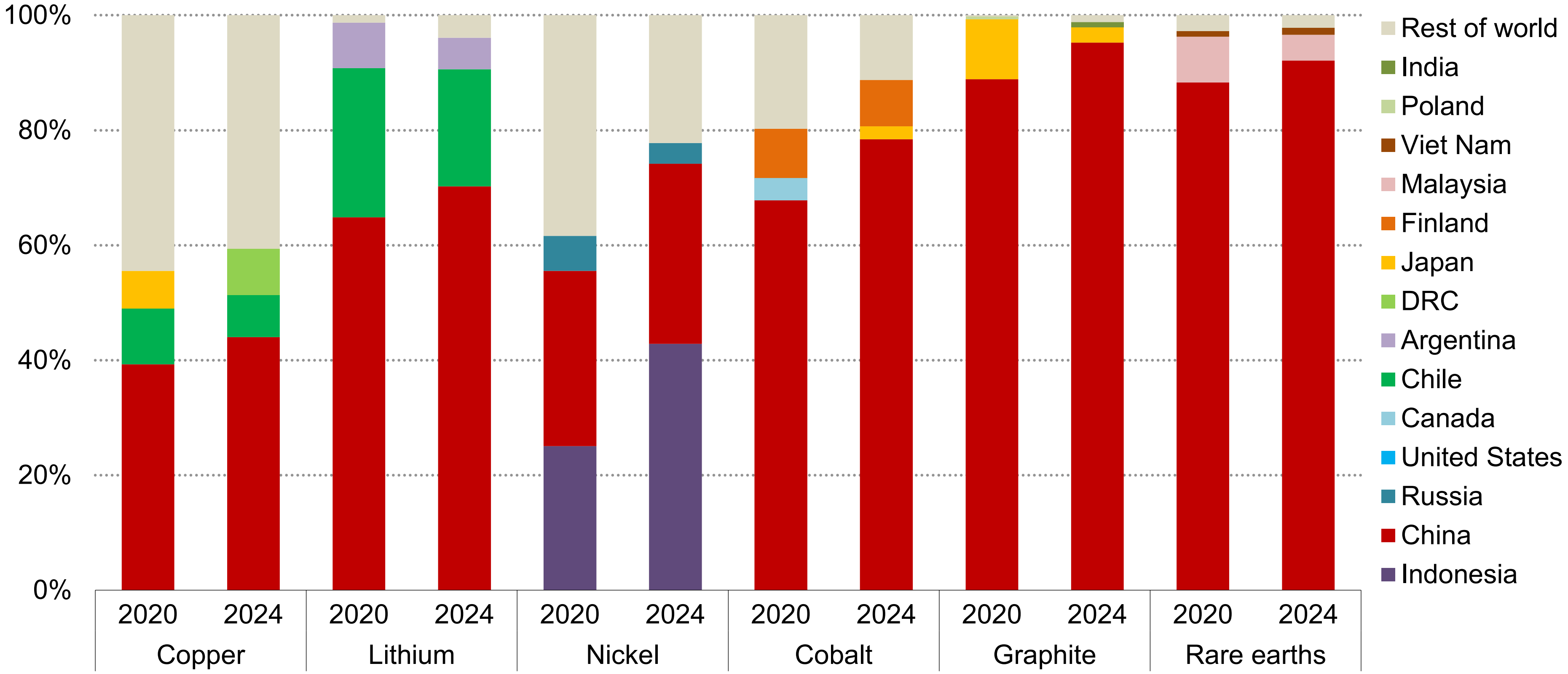
Change in refined material production by country, 2020-2024



Notes: DRC = Democratic Republic of the Congo. The figure illustrates production changes among the top one and two producers compared with the rest of the world.

As a result, geographic concentration of refined products has risen in recent years for nearly all critical minerals, particularly for nickel and cobalt

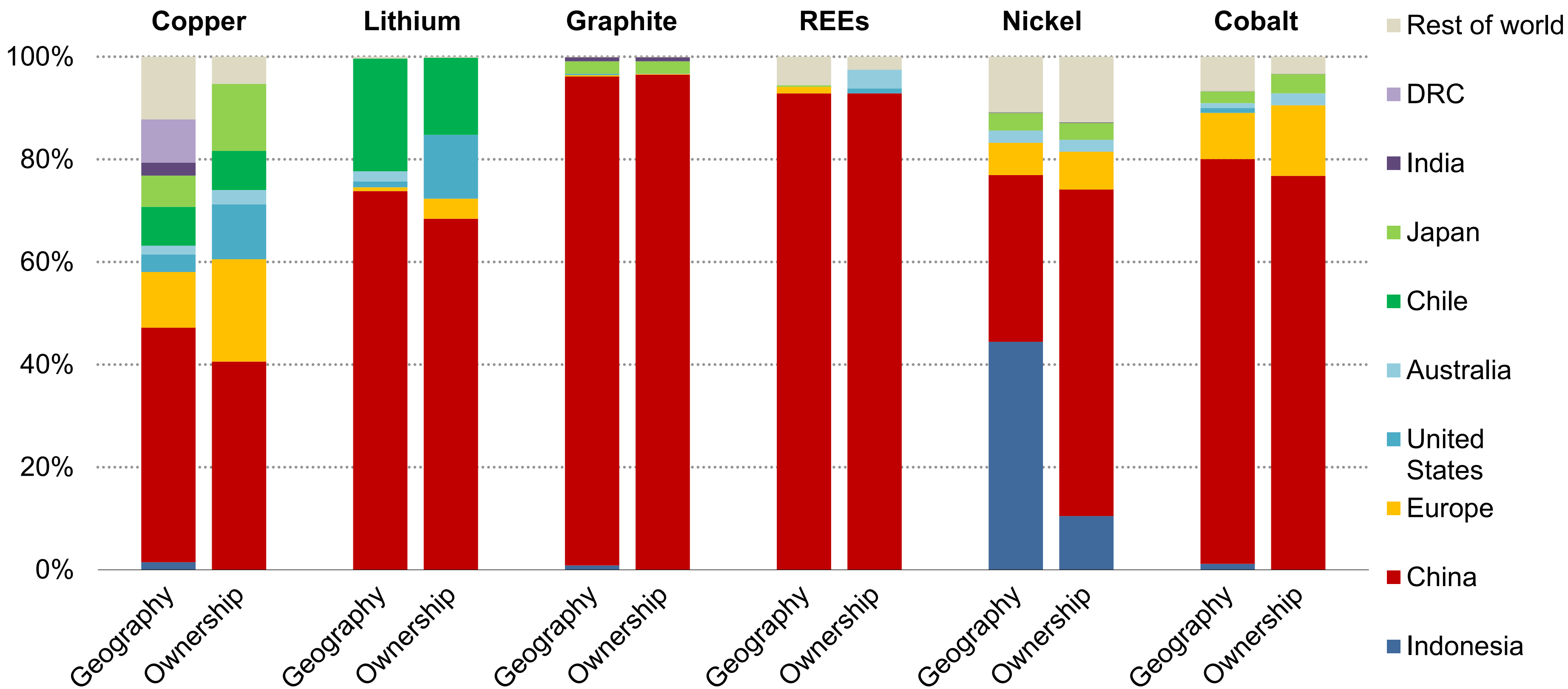
Share of refined material production by country



Notes: DRC = Democratic Republic of the Congo. Graphite is based on battery-grade spherical and synthetic graphite. Rare earths are magnet rare earths only.

China dominates critical mineral refining by both geography and ownership

Refining concentration by geography and ownership, 2024

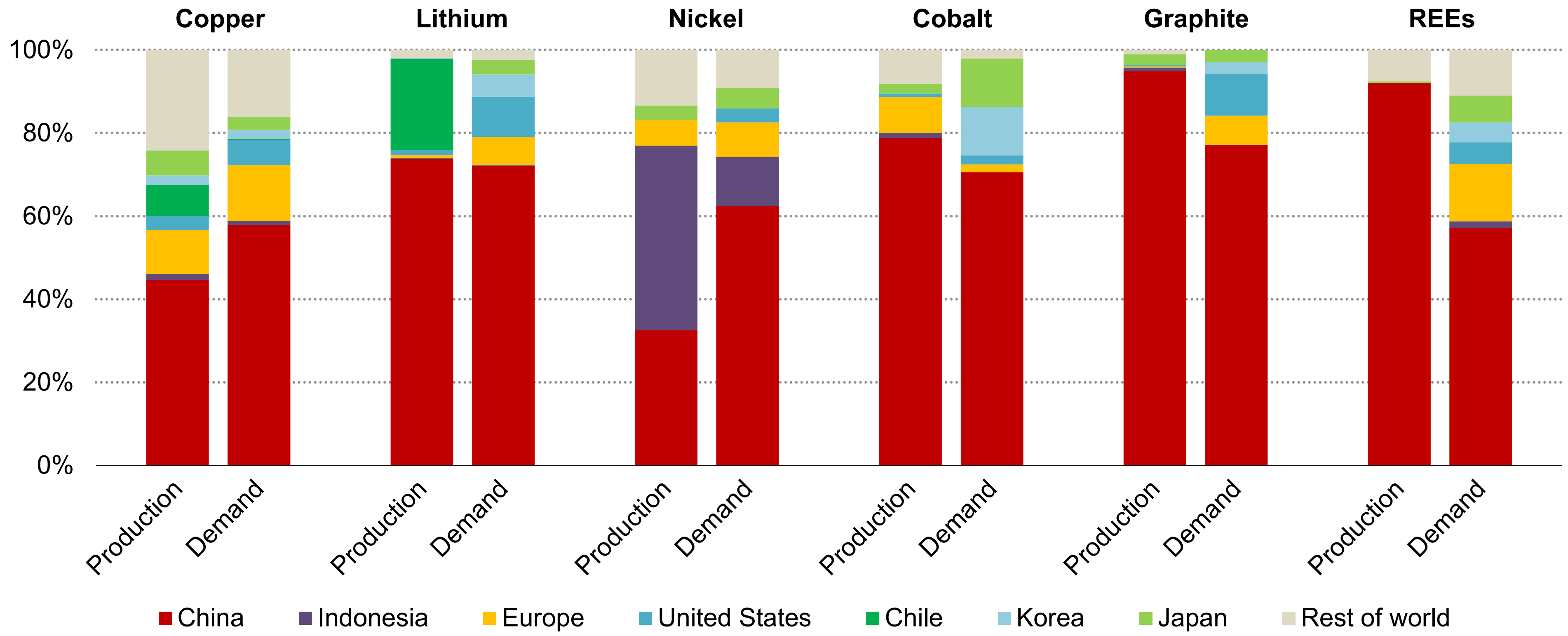


Notes: DRC = Democratic Republic of the Congo. Ownership based on company headquarters location. For projects run by multiple companies, production is assigned to the company with the largest share. For copper, data are on the top 20 mining companies in 2024 representing 56% of production. For lithium, data cover 100% of production in 2024. For rare earths, data cover 94% of production. For nickel, data cover 91% of production. For cobalt, data cover 94% of production. Rare earths are total rare earths.

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

China is by far the largest source of demand for key critical minerals, but Europe, the United States and Japan are also major consumers

Production and demand of refined critical minerals by geography, 2024



Notes: REEs = rare earth elements. Production refers to refined minerals production while demand refers to refined minerals consumption. Rare earths are magnet rare earths only.

Price declines for critical minerals are stymieing efforts to diversify critical mineral supplies

Recent price and investment trends are severely impacting efforts to diversify supply, particularly for refined materials. While production of refined materials has grown substantially to meet rising demand, the vast majority of this expansion has been driven by the dominant suppliers. Between 2020 and 2024, China, the leading refiner of copper and lithium, accounted for approximately 70-80% of supply growth for these minerals, while Indonesia, the top nickel refiner, contributed around 90% of supply growth. For cobalt, graphite and rare earth elements, nearly all production growth was driven by China, further sidelining emerging producers in geographically diverse regions. Although mined output growth followed a similar trend, it remained somewhat less concentrated than refined materials.

As a result, supply diversification for refined materials has made limited progress in recent years, with concentration levels for nickel and cobalt increasing even further. Between 2020 and 2024, the combined share of the top three producers rose from 60% to 80% for nickel and from 80% to 90% for cobalt. Over the same period, the dominance of the top producer has expanded even further across key minerals, with its share increasing from 30% to 43% for nickel and from 68% to 78% for cobalt.

China not only dominates critical mineral refining by geography, but also by ownership. By both geography and ownership, China produces over 95% of battery-grade graphite and rare earths. For rare earths, Australian company Lynas is the one of the only major players outside China today, representing 4% of global refined production in 2024 from its operations in Malaysia. The United States accounted for 1% of the global refined production in 2024 from its refineries in the United States (MP Materials) and Estonia (NP Materials) but is set to play a much larger role in the next decade as new projects come online. China produces 70% of lithium chemicals by geography and ownership and over 40% of copper.

The United States has a much greater role in both refined copper and lithium production by ownership, with its companies owning over 10% of refined copper production and almost 15% of lithium chemical production despite holding 1% of refined production geographically of each. European and Japanese companies also play major roles in refined copper production despite little production domestically, with European companies owning 20% of global production through companies such as Aurubis and Glencore, and Japanese companies owning almost 15% through companies including ENEOS, Mitsubishi Materials and Sumitomo Metal Mining.

Nickel refining by ownership substantially differs from that by geography. While Indonesia is the top nickel refining location by geography with almost 45% of global production, Indonesian companies own only 10% of global production. China owns the vast majority of Indonesian nickel refining assets, with 65% of global refined nickel production by ownership compared with just 30% by geography. This is largely due to big players such as Tsingshan Group and Jiangsu Delong Nickel, which own operations in Indonesia's numerous industrial parks, including Weda Bay and Morowali Industrial Park. Cobalt refining is similar by geography and ownership, with China holding over three-quarters of production for both. Although Europe accounts for only 10% of refined cobalt production, European companies represent a larger share of output, contributing 15% to global refined cobalt production. This is largely due to Umicore's plants in China, Canada and the United States.

While China remains the dominant supplier of all key refined critical minerals by geography or ownership, it also remains the largest source of demand for all key refined critical minerals. China is responsible for over half of global demand for copper, lithium, nickel, cobalt, graphite and magnet rare earth elements. In 2024 copper and nickel were the only refined minerals where Chinese domestic refined demand was greater than domestic refined supply. However, since most of Indonesia's refined nickel supply is owned by Chinese companies, copper remains the only refined material for which China currently has a domestic deficit, with domestic production meeting just 75% of its domestic consumption. In contrast, China has the largest domestic supply surplus for battery-grade graphite and magnet rare earth elements. Therefore, these are key markets where other countries are highly dependent on refined Chinese supply.

This supply concentration by both geography and ownership creates concerns for critical minerals security as disruptions in critical mineral supply can have major impacts on technology prices, inflation, manufacturing and the broader economy.

Amid increasing supply concentration, an expanding number of market restrictions have been introduced in recent years…

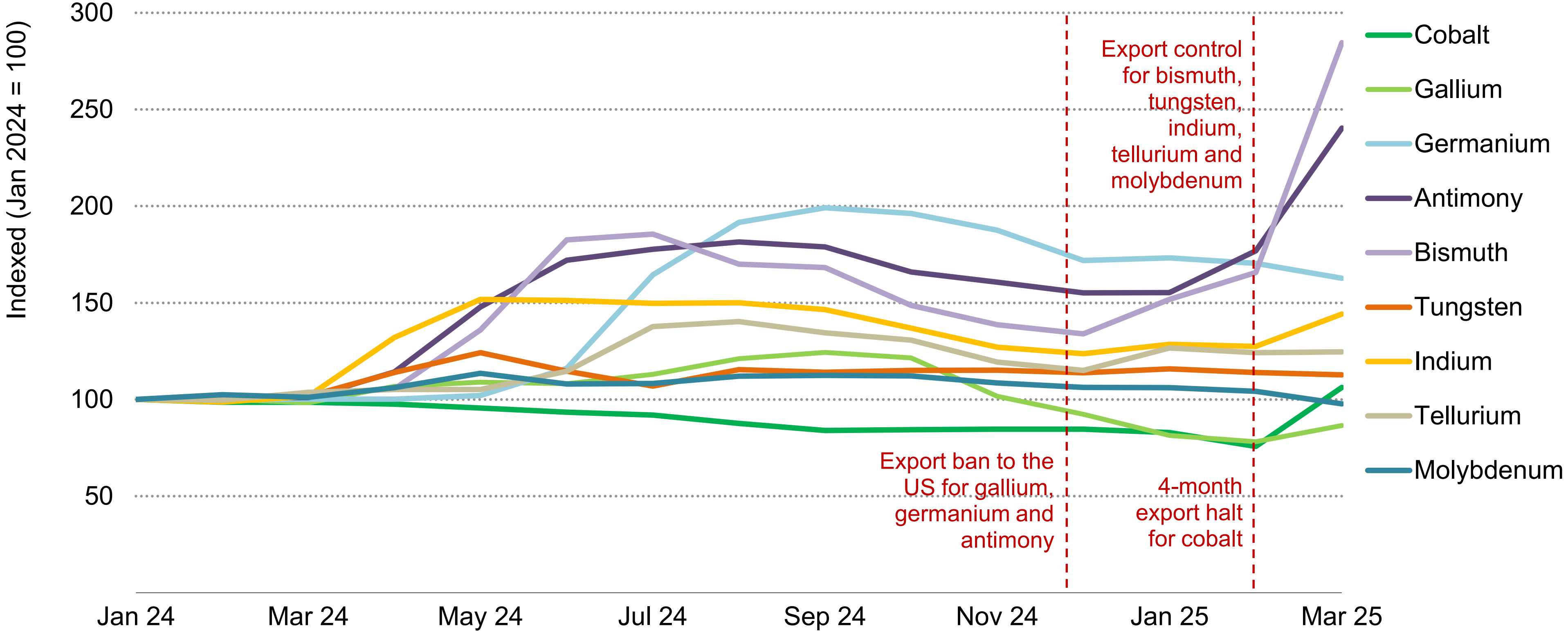
Export restrictions on energy-related minerals since 2023

	By	Market share	Type of control
Lithium	Zimbabwe	9%*	Imposed a ban on raw lithium ore exports in Dec 2022, followed by export licensing requirements for all unprocessed base minerals in Jan 2023
Gallium	China	99%	Export licensing in Jul 2023, followed by an export ban to the US in Dec 2024
Germanium	China	74%	Export licensing in Jul 2023, followed by an export ban to the US in Dec 2024
Antimony	China	74%	Export licensing in Sep 2024, followed by an export ban to the US in Dec 2024
Rare earths	China	92%	Export reporting requirements from Nov 2023 (effective until Oct 2025), followed by export licensing on seven medium and heavy rare earths in April 2025
Graphite	China	98%	Export licensing in Dec 2023
Cobalt	DRC	68%*	4-month halt to exports announced in Feb 2025
Tungsten	China	44%	Export licensing in Feb 2025
Bismuth	China	80%	Export licensing in Feb 2025
Indium	China	70%	Export licensing in Feb 2025
Tellurium	China	77%	Export licensing in Feb 2025
Molybdenum	China	81%	Export licensing in Feb 2025
Nickel	Philippines	9%*	Proposed ban on raw mineral exports in Feb 2025
Rare earths	China	92%	Export ban of rare earth extraction and separation technologies in Dec 2023
LFP cathode	China	98%	Proposed technology export control in Jan 2025
Lithium refining	China	72%	Proposed technology export control in Jan 2025

* Mined output. Notes: LFP = lithium iron phosphate. Market shares are based on refined output in 2024.
Sources: IEA analysis based on USGS (2025), Mineral Commodity Summaries 2025, and EC Raw Materials Information System (accessed April 2025).

… triggering a surge in prices for some materials

Price movement of selected materials subject to export restrictions in recent months



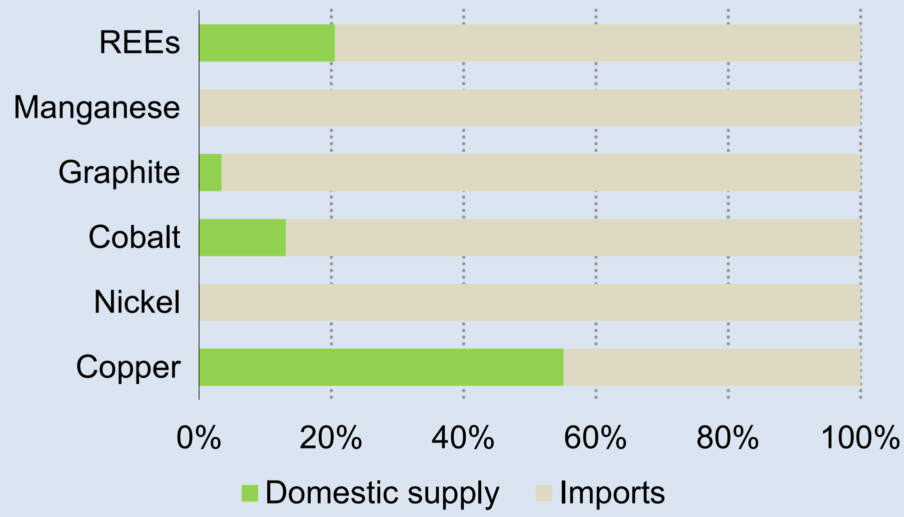
Sources: IEA analysis based on S&P Global and Bloomberg.

Box 1.1 What implications will tariffs and economic uncertainty have for critical minerals?

In April 2025, the United States announced a raft of tariffs on many of its large trading partners as well as a baseline 10% tariff on imports from other countries. Key initial tariff rates included 34% on China, 20% on the European Union, 25% on Korea, 24% on Japan, 26% on India and 10% on the United Kingdom. However, tariffs for many countries were later paused for 90 days until July. Tariffs on China were increased to total 145%, which were subsequently reduced to 30% for 90 days in May. Some products avoided the universal 10% levy but are subject to their own tariff regime, including steel and aluminium, and automobiles and automotive parts. Overall, these announcements marked a significant change in terms of global trade; for the moment it is unclear when and how the picture might change further, as multiple countries are now negotiating with the United States.

Many key critical minerals are currently exempted from tariffs, as the United States is highly reliant on foreign supplies. Copper, lithium, nickel, cobalt, manganese, natural graphite, silicon, rare earth elements and pet coke were all announced as exempt, and in most cases this exemption includes all forms of imports, from ores to refined metals and sulphates. The United States is 100% dependent on imports to meet its demand for refined nickel products and battery-grade manganese sulphate. It also produces

Share of domestic supply of refined critical minerals in the United States



Notes: Nickel = nickel final products including nickel sulphate; cobalt = final refined cobalt products including cobalt sulphate; graphite = battery-grade graphite; manganese = manganese sulphate; REEs = refined magnet REEs.

less than 5% of domestic battery-grade graphite demand and less than 25% of domestic demand for refined cobalt and rare earth elements. In April 2025, a new US Executive Order launched a probe into the need for tariffs on critical minerals. If the investigation finds imports of processed critical minerals, including derivative products, impair national security, specific tariffs may be applied. This builds on a previous probe ordered in February into copper imports with tariffs being a potential outcome.

Although the direct effects of tariffs are limited for the moment, critical mineral markets could nonetheless be affected by broader economic uncertainty, as well as policy moves that could weaken US consumer demand for EVs and battery storage. Coupled with higher prices from tariffs on Chinese batteries (80% of global battery production) and higher domestic battery manufacturing costs, this could slow battery critical minerals demand, including lithium, nickel, cobalt and graphite. The copper market is also tied to the health of the global economy and industrial activities, being driven by construction, energy technologies and industrial equipment. Lower short-term demand could amplify longer-term risks on the supply side by deterring or delaying new supply investment.

In 2024 over 90% of lithium-ion battery storage cells deployed in the United States were from China, almost entirely consisting of lithium iron phosphate (LFP) cells which are not produced anywhere else at scale. With the new tariffs, Chinese LFP cells now face effective tariffs over 40%, amid limited domestic US manufacturing capacity. Some of this may be absorbed by Chinese players reducing margins, however, as things stand, the likely outcome is to drive up costs for utilities and/or to delay deployment. This may also result in Chinese batteries and energy technology products being pushed to other markets such as Europe and Southeast Asia.

If the new tariffs are maintained for an extended period of time, there is the potential for the creation of a segmented market for energy technologies. High tariffs on China-dominated products like LFP batteries would raise the price floor in the United States, shielding the domestic market from competition with Chinese imports. This could help de-risk domestic production projects.

Nevertheless, the uncertainty over tariffs and the broader economic outlook is creating a challenging environment for investors, potentially deterring some critical mineral supply projects, including for minerals like copper and lithium which face medium-term supply deficits. This is a particular issue for copper, where large, capital-intensive projects require strong market confidence. Diversified players may be disproportionately affected, as dominant actors are better positioned to weather price volatility.

Critical minerals have become a strategic priority for economic security

Amid rising supply concentration, a wide range of export control measures on critical minerals were announced in recent years. In September 2024, China announced that it would impose export restrictions on antimony, a key material for semiconductor and munition production. The European Union has been particularly affected, with no antimony exports to the region since October 2024. This has sparked shortage concerns across EU defence, energy and automotive industries, prompting a search for alternative suppliers.

Later, in December 2024, China announced a complete ban on exports of gallium, germanium and antimony to the United States. China simultaneously announced that it would tighten review of graphite exports to the United States based on intended end use, building on the export controls that China introduced for specific graphite products in 2023. Under these export controls, exporters must apply for permits to ship graphite materials, including those essential for EV and storage batteries.

China's December 2024 export controls were followed by additional export controls in February 2025 on a range of materials including tungsten, tellurium, bismuth, indium and molybdenum – key minerals primarily used in defence and high-tech applications. Amid rising trade tensions, China announced the implementation (with immediate effect) of export controls on seven medium and heavy rare earth-related items (samarium, gadolinium, terbium, dysprosium, lutetium, scandium and yttrium) in April 2025.

The effect of Chinese export controls on mineral prices has been varied. Following China's February 2025 export controls, prices for some materials spiked. For example, bismuth prices increased by nearly 90% to all-time highs in March 2025, given China's dominant share in production. However, for some other materials, prices did not increase significantly following China's introduction of export controls. For example, in the case of germanium, prices had already increased following China's announcement of export licensing requirements in 2023, meaning the December 2024 export ban to the United States did not cause a major price spike. Similarly, after China introduced export controls on gallium and germanium in 2023, market speculation that indium could be targeted next drove prices higher in 2024. Indium prices accordingly saw only a modest increase following China's official export control announcement in February 2025.

Meanwhile, in February 2025, the DRC, the world's largest cobalt supplier, announced a four-month suspension of cobalt exports to curb falling prices. This drove a surge in cobalt prices – at their peak on 13 March, prices had increased by 67% since the announcement of the export ban – with ripple impacts on prices for cathode materials.

Export controls are not only limited to raw materials, but are also increasingly targeting specific technologies. In January 2025, China's Ministry of Commerce proposed a new set of export licence restrictions on technologies related to LFP cathode material production and lithium processing, which is under public consultation (see Chapter 3 for further analysis on this announcement). These proposed export controls follow China's December 2023 export ban on rare earth extraction and separation technologies.

Export controls in China and the DRC have been accompanied by tariff measures in consuming countries, even before the major tariff announcements in 2025 (see box 1.1). In May 2024, the United States imposed import tariffs on several Chinese products, including critical minerals, EVs, solar cells and semiconductors. Canada followed suit in October 2024 by imposing a 100% import surtax on Chinese-made EVs and announcing consultations concerning potential tariffs on batteries, semiconductors, solar products and critical minerals.

Amid these developments, many economies are increasingly deploying efforts to accelerate the development of mineral projects, including through substantial public funding. In the United States, measures are being introduced to boost domestic production and secure US offtake of mineral resources in foreign countries. In March 2025, the US President issued an executive order titled Immediate Measures to Increase American Mineral Production that includes expedited permitting approval and the creation of a special fund for investments in domestic critical mineral projects. Canada and Australia have similarly established multiple financing programmes. In the European Union, the European Commission recently designated 47 projects as "strategic" pursuant to the EU Critical Raw Materials Act, enabling these projects to benefit from streamlined permitting provisions, easier access to finance and support to connect with relevant off-takers. In the Middle East, Saudi Arabia has established a USD 182 million mineral exploration incentive programme, while Qatar's sovereign wealth fund has invested around the same amount into the US-backed Techmet fund. These funding measures reflect the importance that countries place on securing critical mineral supplies.

Mineral diplomacy has also become a crucial priority for securing the critical mineral supply chain, with countries forming partnerships focused specifically on critical mineral resources. Canada, France, Germany, the United Kingdom and the United States have all concluded multiple mineral bilateral partnerships with a range of mineral-producing and mineral-consuming countries. The European Commission, for its part, has signed raw material partnerships with 14 countries and has recently launched the Clean Trade and Investment Partnerships to develop cleaner value chains, with negotiations with South Africa commencing in March 2025 with an emphasis on critical mineral supply chains. In the Middle East, this trend is exemplified by the international mineral partnerships of the United Arab Emirates, including with the DRC, Kenya and Zambia. The increasing number of critical mineral partnerships reflects a growing recognition that securing mineral supply chains requires international co-ordination and collaboration between mineral-producing countries and mineral-consuming countries. These emerging international partnerships have the potential to shape trading relationships in the future, with companies choosing to follow government signals in their investment and sourcing decisions (see Chapter 4 for further analysis on regional policy developments).

Governments worldwide are also asserting greater control over domestic mineral supplies through the establishment of traceability systems. China has implemented a comprehensive traceability system for rare earth elements, while Indonesia has established the SIMBARA system for mineral tracking. In Africa, several nations have launched traceability initiatives, such as the Zambia Integrated Mining Information System (ZIMIS). These systems serve multiple purposes: they help prevent illegal mining and trading, enhance tax collection and allow governments to have more control over domestic mineral supplies. When carefully designed and implemented, traceability mechanisms have the potential to reduce supply chain disruptions and contribute to the development of sustainable and responsible mineral supply chains (see box 1.4). The potential for traceability systems to contribute to sustainable and responsible mineral supply chains was highlighted in the recent report of the United Nations Secretary-General's Panel on Critical Energy Transition Minerals, which calls for the development of a global traceability, transparency and accountability framework along the entire mineral value chain.

Meanwhile, resource-rich countries are implementing policies to retain greater economic value from their mineral resources. Indonesia's 2020 ban on nickel ore exports has inspired similar measures in the DRC and the Philippines and Zimbabwe. These policies are meant to incentivise domestic processing of minerals before export, often in combination with local ownership requirements. There is a similar focus on downstreaming capabilities in the Middle East, with the United Arab Emirates' plan to develop a lithium processing plant, as well as in Latin America, where Bolivia plans to ramp up lithium extraction and processing with Russian and Chinese partners.

Critical mineral supply chains are increasingly viewed through a national security lens across major economies. The critical minerals sector has evolved to become a strategic domain where policy, security and economic considerations are intertwined. Market participants need to ensure that their strategies are aligned with this new landscape.

Box 1.2 Deep-sea mineral resources: what comes next?

Growing demand for minerals and corresponding concerns over geographical concentration of supply have led to increasing interest in marine mineral deposits. These deposits, found in the deep seabed lying at depths exceeding 200 metres, contain sizeable quantities of key minerals such as nickel, cobalt and copper, often at higher grades than terrestrial mineral reserves.

However, the majority of deep-sea mineral resources lie in areas beyond national jurisdiction, referred to as "the Area". The Area falls under the governance of the International Seabed Authority (ISA), established under the 1982 United Nations Convention on the Law of the Sea (UNCLOS) and the 1994 agreement relating to its implementation. Under this framework, the ISA is the organisation through which parties to UNCLOS organise and control mineral-related activities in the Area.

To date, the ISA has issued over 30 exploration contracts, covering more than 1.5 million square kilometres of the seabed. These permits are held by a mix of state entities, state-sponsored companies and private contractors. While exploration efforts have advanced significantly, including the collection of geological and environmental data, no commercial exploitation has yet occurred.

The ISA is currently in the process of developing the regulations that will govern exploitation of these resources. These proposed regulations, which will form part of the Mining Code, aim to address issues such as environmental protection, financial terms, liability, compliance and benefit-sharing in contracts.

Negotiations are taking place amid growing divergence among countries. As of April 2025, 32 states support a ban, moratorium or precautionary pause on deep-sea mining, citing the absence of a robust regulatory framework and insufficient scientific understanding of the environmental impacts of deep-sea mining. Others are pushing for commercial extraction, emphasising the strategic importance of seabed minerals and the need to establish legal certainty for investors.

At the first part of its 30th Annual Session in March 2025, the ISA Council completed a second reading of just over half of the draft exploitation regulations. However, several politically and technically complex issues remain unresolved. These include: agreement on financial terms and a royalty regime; the definition and assessment of environmental harm; the role of regional environmental management plans; the structure and authority of compliance and enforcement mechanisms; and the finalisation of environmental standards and guidelines.

Provisions concerning liability and the operationalisation of an environmental compensation fund are also under active negotiation.

The second part of the ISA's 30th Annual Session, scheduled for July 2025, is expected to focus on these issues. Discussions are anticipated to cover the definition of "effective control" of contractors, the responsibilities of sponsoring states, and the rights of adjacent coastal states. The ISA has also proposed the formation of new informal working groups to accelerate convergence on contentious areas of the text. These groups will operate in parallel with existing intersessional processes, with the objective of transitioning from technical drafting to more explicit political negotiation.

A key point of contention is the legal status of mining applications in the absence of agreed regulations. This issue has gained urgency since Nauru triggered the "two-year rule" under UNCLOS in 2021. The rule obliges the ISA to consider applications for exploitation even if regulations have not been finalised, based on existing UNCLOS provisions and any provisionally adopted rules.

Although the two-year deadline expired in July 2023, the ISA Council has resolved that no commercial exploitation should commence until a complete regulatory framework is in place. However, at the March ISA meeting, members reminded the council that this decision is inconsistent with the UNCLOS's binding provisions.

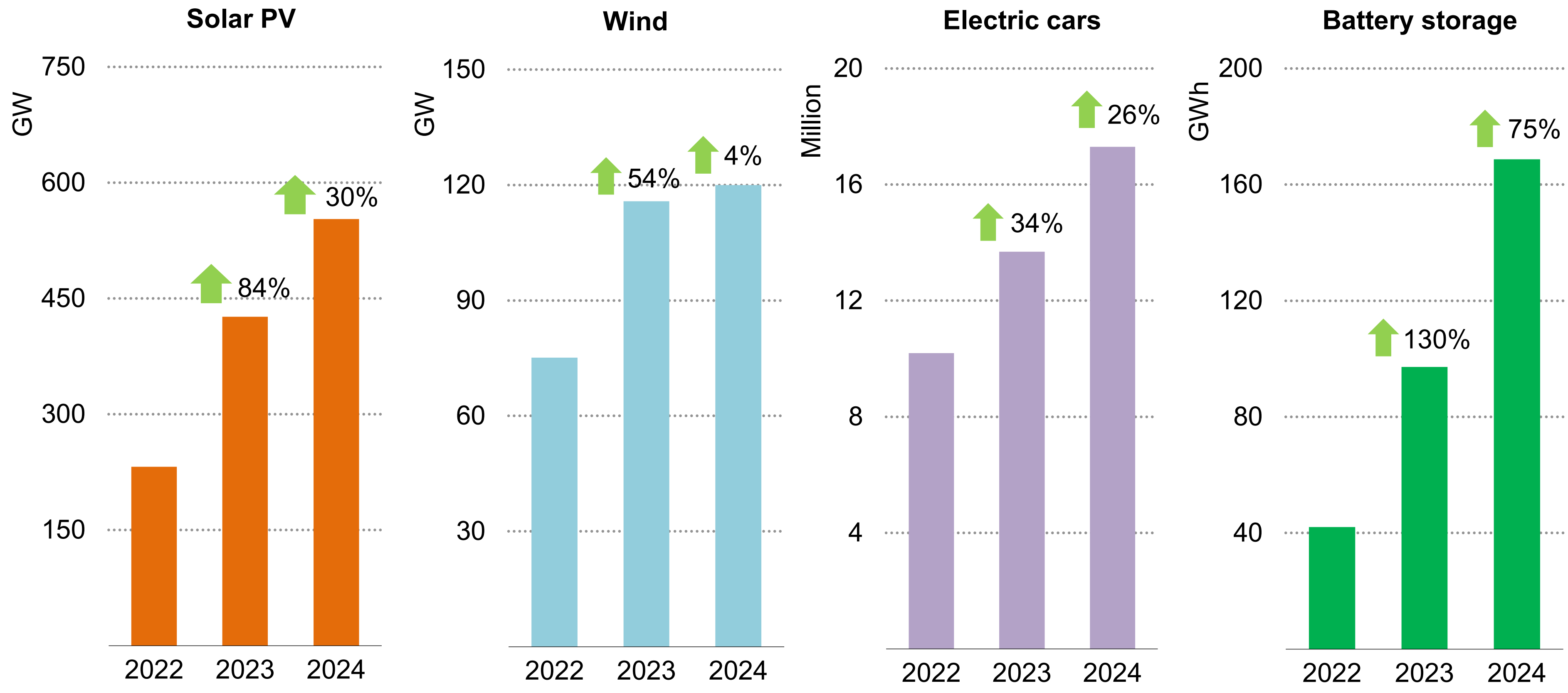
Towards the end of the March ISA Council meeting, The Metals Company (TMC) reiterated its intention to submit an ISA exploitation application in June 2025 via its subsidiary, Nauru Ocean Resources Inc., under the state sponsorship of Nauru. In parallel, TMC announced that it had initiated a process to apply for seabed mining permits under existing United States domestic legislation, given that the United States is not a party to UNCLOS. In April 2025, the US President issued an Executive Order directing government agencies to support the development of seabed mineral resources from in areas within and beyond national jurisdiction.

The outcome of the July 2025 ISA session will be critical. If member states can agree on key elements of the draft exploitation regulations, the ISA could move towards adopting a regulatory framework that provides the legal basis for assessing future applications. If not, the council will need to decide whether and how to consider applications for exploitation in the absence of completed rules.

Downstream market trends

Deployment of renewables, electric cars and energy storage continued to rise in 2024

Annual capacity additions for selected energy technologies



Note: PV = photovoltaic; GW = gigawatts; GWh = gigawatt-hour.

Renewables deployment continued its upward trend in spite of some challenges

In 2024, global annual renewable capacity additions surged by an estimated 25%, rising to around 700 GW. Solar photovoltaic (PV) accounted for over three-quarters of the capacity additions, followed by wind (17%). Together, solar PV and wind accounted for 95% of overall renewable capacity growth in 2024. China once again led the global capacity expansions, making up almost two-thirds of total renewable capacity connected to the grid in 2024. The country surpassed its 2030 ambition of 1 200 GW of combined solar PV and wind capacity six years early in mid-2024.

Solar PV

Solar PV additions in 2024 rose by almost 30% compared with 2023, totalling about 550 GW. In China, solar PV capacity additions reached over 340 GW, up 30% from the previous year. Utility-scale projects led the growth, while residential installations declined to under 10% of new additions as incentives were phased out.

The European Union installed around 60 GW of solar PV capacity, similar to 2023 levels, but double the annual capacity added in 2021, before the energy crisis sparked by the Russian Federation's (hereafter, "Russia") invasion of Ukraine in 2022. High electricity and gas prices and new incentives in the aftermath of the invasion had driven rapid growth in recent years. However, outside of three largest markets (Germany, Italy and Spain), annual PV additions declined in over 15 member states in 2024, as lower energy prices and reduced policy support slowed growth.

Globally, three major solar PV markets saw record levels of expansion: the United States, India and Brazil. In the United States, almost 50 GW of new solar PV capacity was added to the grid, breaking the previous record seen in 2023. India installed around 30 GW of solar PV in 2024, almost tripling its growth from 2023. Brazil added over 16.5 GW, surpassing a total capacity of 50 GW in 2024, thanks to large utility-scale additions supplementing the continued roll-out of distributed resources driven by a net metering scheme.

In terms of electricity generation, renewables alone made up almost three-quarters of the global increase in 2024. The contributions from solar PV led the way, boosting electricity generation by about 480 terawatt-hours (TWh) year-on-year – more than any other energy source and well above the previous year's increase. Global generation from solar PV has been doubling approximately every three years since 2016 and it did so once again from 2021 to 2024.

The growth in solar PV deployment over the last decade has resulted in a corresponding growth in the demand for silicon, silver and copper, among other minerals. Demand for silicon for use in solar PV expanded over fivefold and that for silver grew nearly sevenfold between 2015 and 2024.

Wind

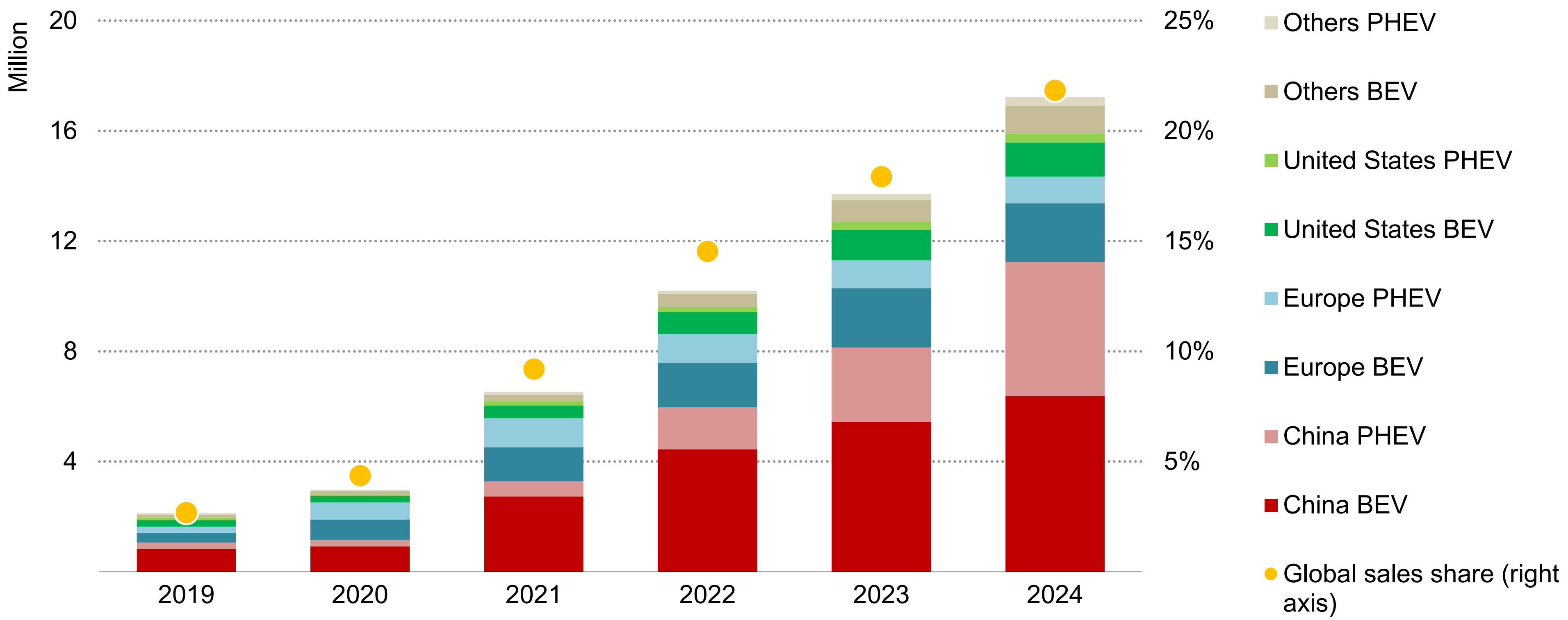
For wind, annual additions remain stable from those seen in 2023 at around 120 GW. Electricity generation from wind expanded by around 180 TWh with new projects being brought online. Nevertheless, given the high base level of 2023 that followed a 54% growth over 2022, the annual growth in 2024 slowed noticeably, as the industry continues to face permitting and licensing challenges in several regions.

China's wind capacity additions increased only slightly in 2024 but remained strong with 80 GW of new capacity installed. On the other hand, wind additions in the European Union declined by 20% even as wind energy contributed to 20% of all electricity consumed in the region. Long permitting timelines, grid connection bottlenecks, supply chain challenges and auction schedules were among key reasons for lower wind additions. In the rest of the world, capacity additions of 3.4 GW in India exceeded those seen in 2023, while the United States and Brazil saw a decline from last year's levels. The sector faces a combination of growing global macroeconomic challenges and domestic policy barriers in 2025.

The growth in wind deployment over the last decade has resulted in a corresponding growth in the demand for magnet rare earth elements (neodymium, praseodymium, dysprosium and terbium) used in the motors of wind turbines. Demand for magnet rare earths for use in wind turbines (excluding their use in other clean energy technology applications, such as electric vehicles) expanded around threefold between 2015 and 2024.

Global electric car sales surpassed 20% global sales share, reaching 17 million in 2024

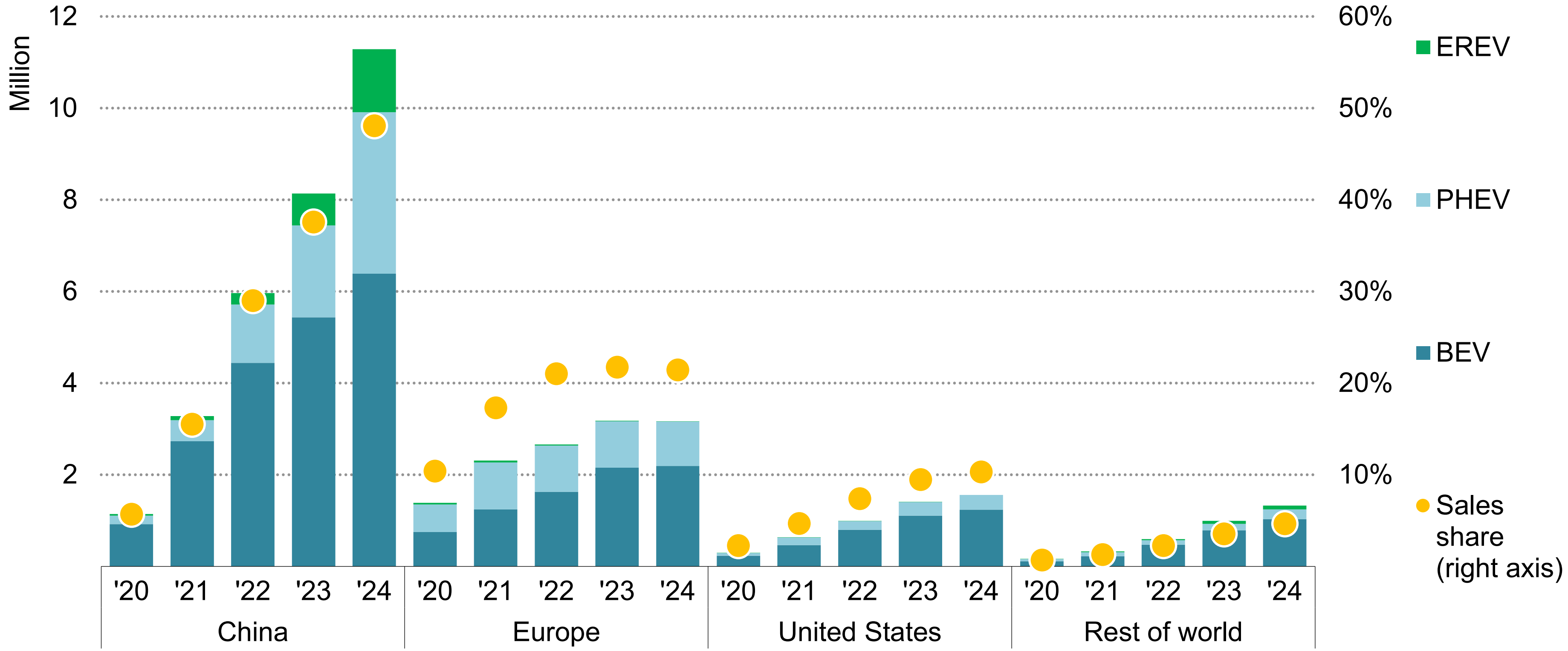
Electric car sales by mode and region



Notes: BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle.
Source: IEA (2025), Global EV Outlook 2025.

Growth in electric car sales slowed somewhat in Europe and the United States, but remained strong in China and the rest of the world

Electric car sales by mode and region



Notes: BEV = battery electric vehicle; PHEV = plug-in hybrid vehicle, EREV = extended-range electric vehicle. EREVs are a type of PHEV.
Source: IEA (2025), Global EV Outlook 2025.

Despite slower growth in some markets, robust growth in EV sales is set to continue, driven by increasing cost-competitiveness

Global electric car sales exceeded 17 million in 2024, a 25% year-on-year increase. China remained the leading market for electric cars, and sales continued to grow in the United States. However, global sales were somewhat tempered by stagnating sales growth in Europe as subsidies were phased out in several major markets. Significantly, sales outside the leading markets – China, Europe and the United States – experienced a record increase in sales, closing in on the sales in the United States.

China remained the world's largest electric car market in 2024 with over 11 million electric cars sold, representing nearly two-thirds of global electric car sales. Around half of all vehicles sold in China in 2024 were electric. Since July 2024, sales of electric cars in China have overtaken conventional car sales on a monthly basis. In China, 2024 remains the fourth consecutive year during which the electric car sales share grew by around 10% year-on-year. The growth of battery electric car sales in 2024 in China partly reflects their growing price competitiveness with conventional cars, further supported by a trade-in scheme introduced in April 2024. The scheme provided increased financial support for consumers replacing an old conventional vehicle with an electric car. In 2024, more than a third of new domestic electric car sales benefited from the scheme.

Europe remained the second-largest market for electric cars with 3.2 million vehicles sold in 2024, almost 20% of global sales. About one in five new cars sold in Europe was electric in 2024. In over half of 27 EU countries, the electric sales share increased, while it stalled or decreased in the rest. Both Germany and France saw a drop in electric car sales share in 2024, primarily the result of subsidies being phased out. Germany ended its subsidies at the end of 2023, while France has progressively scaled back its subsidies – reducing the environmental bonus available to higher-income buyers and limiting eligible models. Nevertheless, the electric sales share increased in other major markets. In the United Kingdom, the second-largest car market in Europe, the electric sales share reached 30% in 2024, up from 24% in 2023, benefiting from the start of a vehicles emissions trading scheme. Norway reached 91% electric car sales share, and Denmark hit 56%.

In the United States, electric car sales reached 1.6 million in 2024, growing by 10%, with its global market share growing to almost 10%. There was a 15% increase in model availability compared with 2023, increasing choices for consumers. The Tesla Model Y and Model 3 have been the top-selling models in the United States since 2020; however, the significant expansion of new models available has reduced Tesla's domestic market share from 60% in 2020 to 38% in

2024. Moreover, 2024 was the first year in which Tesla saw a decrease in sales, compensated by rising sales from other automakers. The Clean Vehicle Tax Credit was modified in 2024 to provide instant direct subsidy for EV purchase at point of sale, likely supporting sales, combined with other incentives from 27 states promoting electric car adoption.

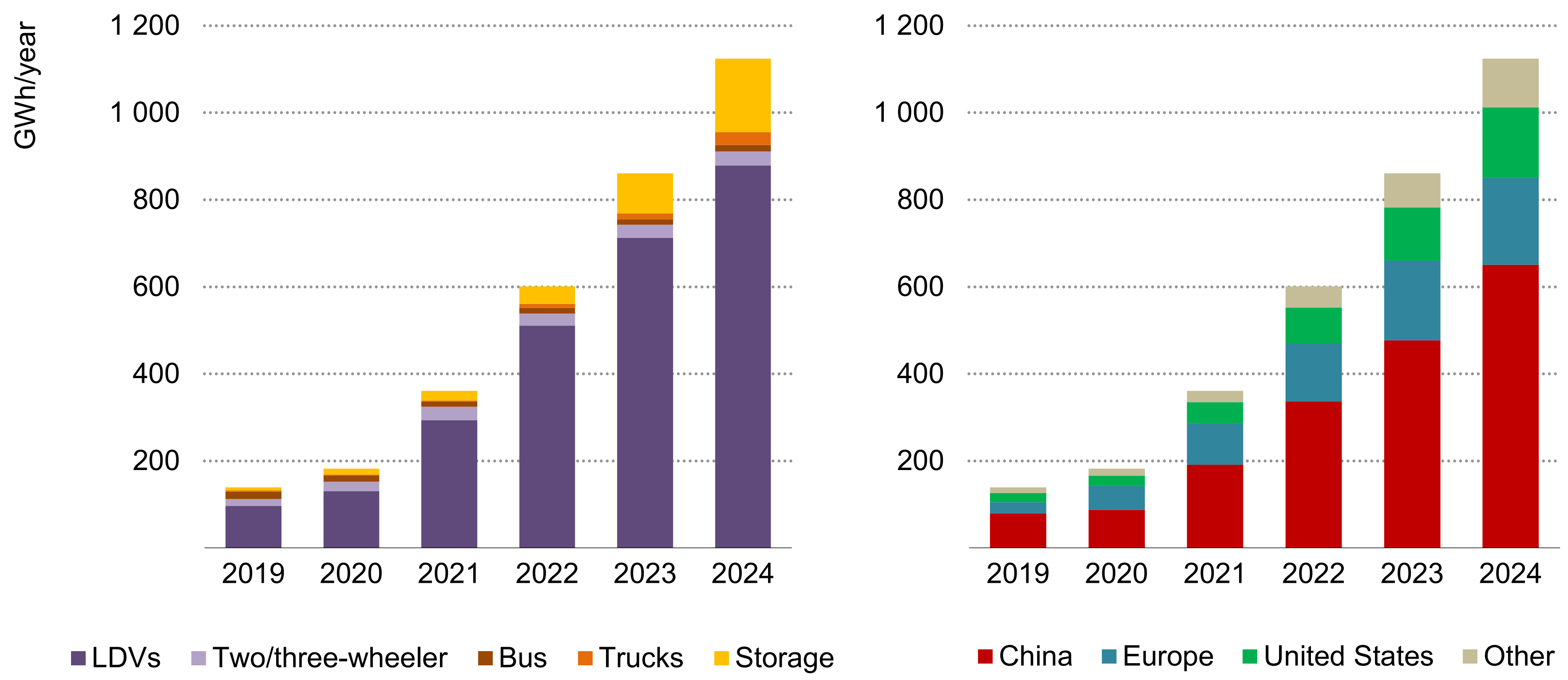
In the rest of the world there was a record increase in electric car sales, reaching 1.3 million in 2024, almost matching that in the United States, with a sales growth of almost 35%. Emerging markets in Asia saw the largest increase in sales, with a 40% growth year-on-year. In India total sales reached 100 000 with sales share slightly increasing. Thailand remained the largest market in Southeast Asia, though sales dropped from last year. Viet Nam and Indonesia saw strong growth, tripling and doubling their sales respectively from the previous year, with Viet Nam almost reaching 20% electric sales share. In other regions, Brazil stood out, more than doubling sales from 2023. Rapid growth in emerging markets has been supported by policy incentives, high fuel prices and affordable electric cars primarily from Chinese original equipment manufacturers (OEMs). The development of new local brands has also supported sales in these regions, such as VinFast in Viet Nam, which has also started to export to other regions such as Indonesia, Malaysia and the United States. Chinese exports of electric cars have supported sales in these regions; for instance, in Thailand, Chinese imports make up 85% of electric car sales. However, temporary import tariff exemptions for many of these countries are ending or are conditional on OEMs committing to developing EV manufacturing in their countries, driving Chinese OEM manufacturing announcements for Brazil, Indonesia, Malaysia and Thailand.

In recent years, sales of plug-in hybrid electric vehicles (PHEVs) have grown faster than battery electric vehicles (BEVs) in China. The sales share of PHEV cars in total electric car sales increased to over 35% in 2024. In China, there has also been a growing trend towards extended-range EVs (EREVs). EREVs are vehicles with an electric powertrain but also have a combustion engine that has the sole function of charging the battery when the charge is low. EREVs have much larger batteries than PHEVs, often around twice the size. The share of EREVs within the Chinese electric car market has quadrupled since 2021, exceeding 10% in 2024. This accelerating trend towards PHEVs and EREVs has decreased the BEV share of total electric car sales from 70% in 2020 to below 60% in 2024. Despite this, battery electric car sales have increased over fivefold over the same period, demonstrating their continued popularity.

Although growth rates in EV sales have slowed in some markets, sales remain generally strong. As the market matures and subsidies are phased out, growth rates have tempered in some regions. However, robust growth in EV sales is expected to continue in the near and long term, supported by increasing cost-competitiveness, ongoing policy momentum, major increases in manufacturing capacity, and particularly from expanded adoption in developing economies.

Global battery demand surpassed the 1 terawatt-hour milestone in 2024

EV and storage battery demand by mode and region, 2019-2024

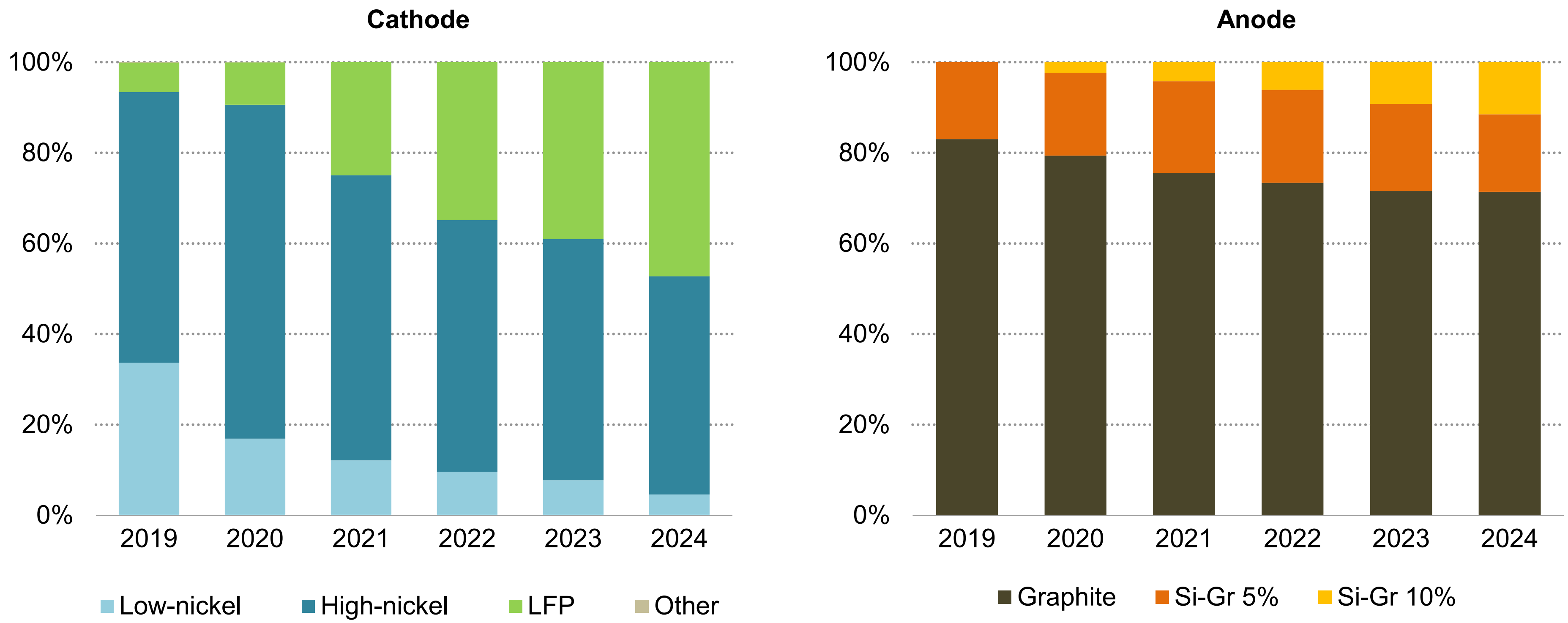


Notes: LDVs = light-duty vehicles; GWh = gigawatt-hours. Battery demand reflects the batteries installed in vehicles sold in each region, and not the battery demand for vehicles manufactured in each region. Electric vehicle and battery stockpiling are excluded from the analysis.

Source: IEA analysis based on EV Volumes.

LFP now supplies almost half the global electric car market

Electric car battery cathode and anode chemistries sales share, 2019-2024

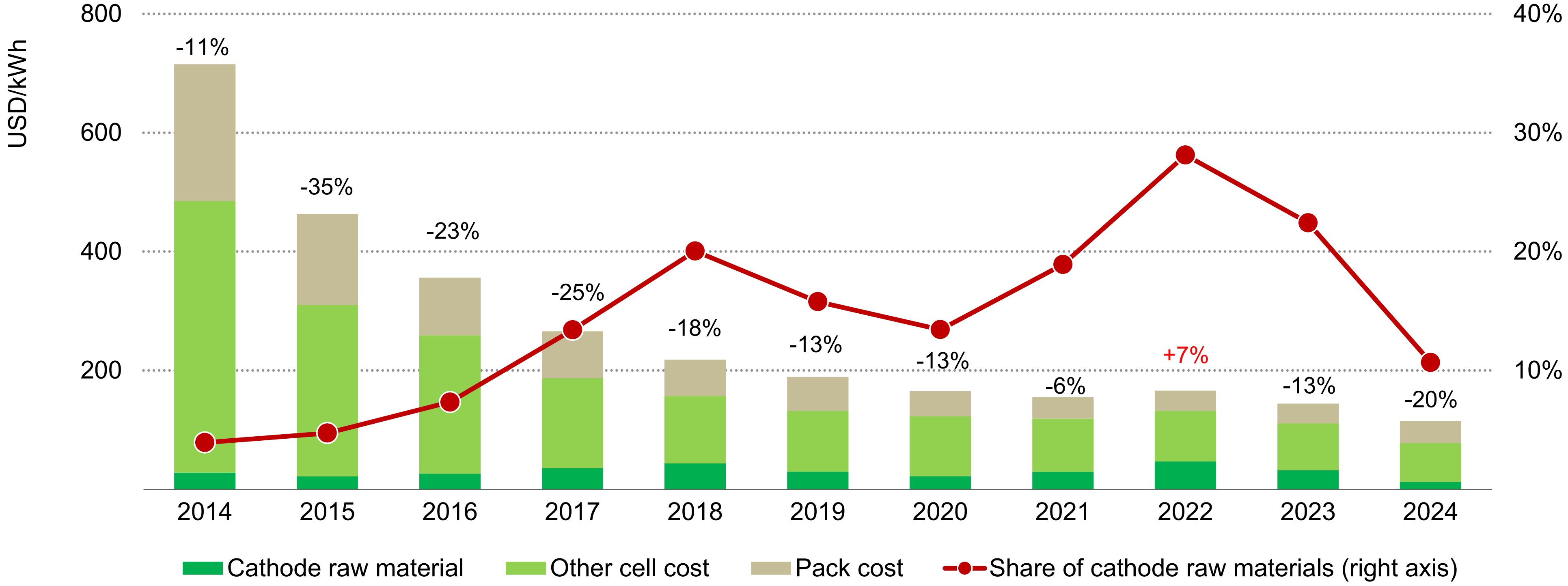


Notes: Si-Gr = silicon-doped graphite with % of silicon content. Low-nickel includes NMC333 and NMC532 (NMC = lithium nickel manganese cobalt oxide). High-nickel includes: NMC622, NMC721, NMC811, nickel cobalt aluminium oxide (NCA) and nickel manganese cobalt aluminium oxide (NMCA). Sales share is based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

Source: IEA analysis based on EV Volumes, BloombergNEF and China Automotive Battery Industry Innovation Alliance.

Battery pack prices hit record lows driven by the fall in critical minerals prices

Global average lithium-ion battery pack price and share of cathode raw material cost, 2014-2024

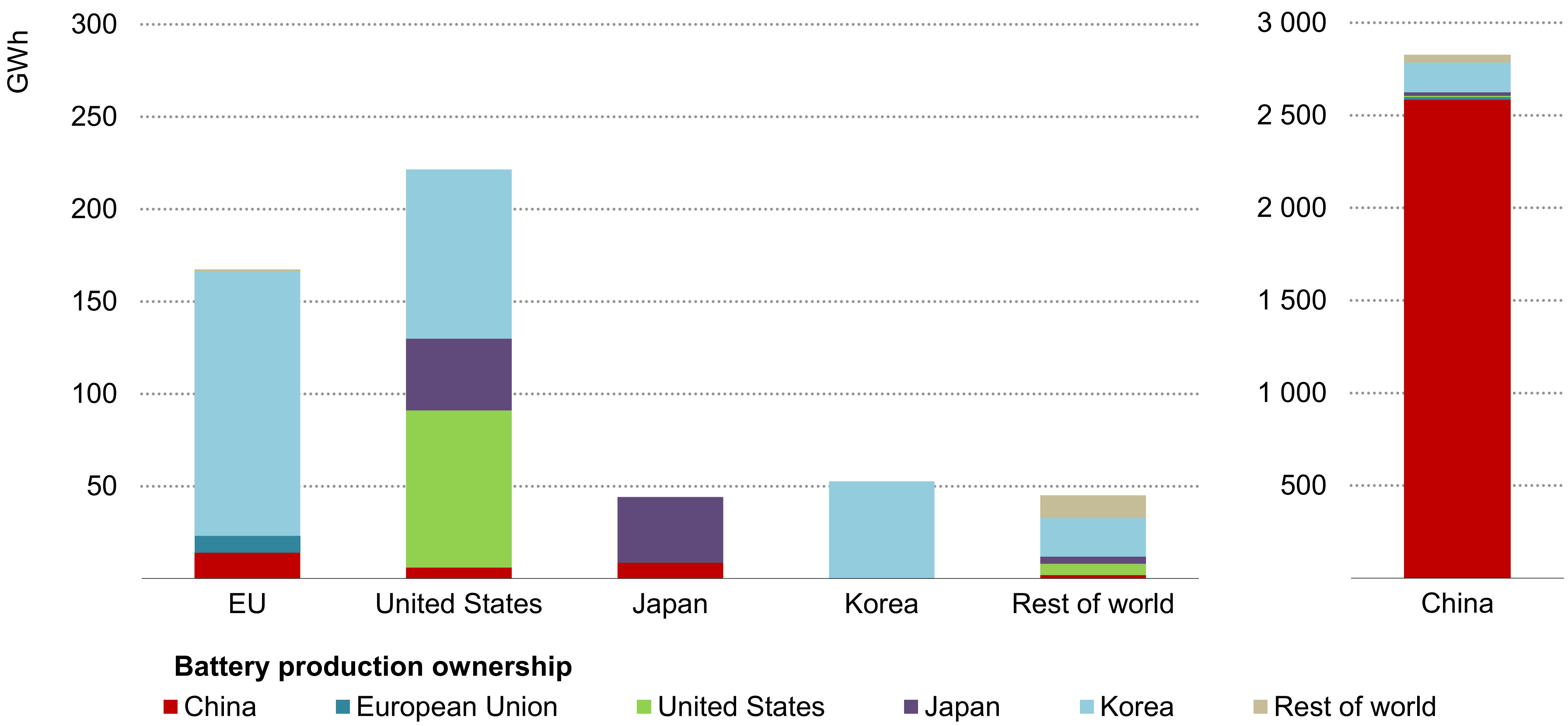


Notes: kWh = kilowatt-hour. Cathode material costs include lithium, nickel, cobalt and manganese. Other cell costs include costs for anode, electrolytes, separator and other components as well as costs associated with labour, manufacturing and capital depreciation. Percentages on bars show year-on-year total global average battery pack price change. Analysis includes all cathode chemistries and global chemistry sales shares.

Source: IEA analysis based on BloombergNEF.

Korean battery manufacturers have the largest overseas battery production capacity

Installed lithium-ion battery cell nameplate manufacturing capacity by geography and ownership, 2024

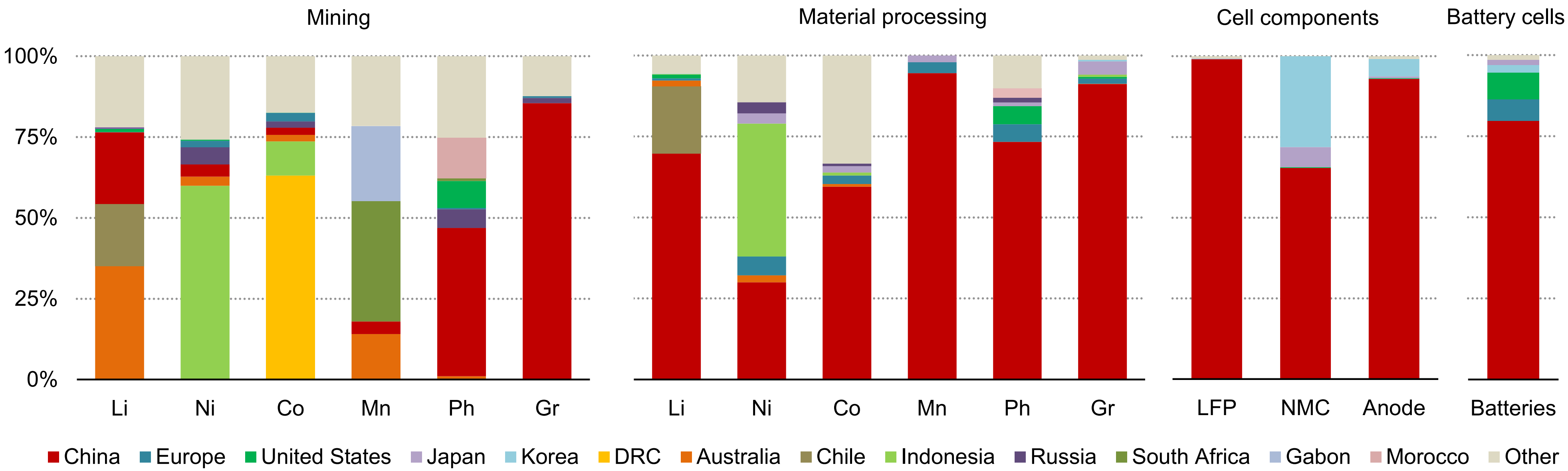


Notes: Based on company headquarters location. The manufacturing capacity of joint ventures between automakers and battery producers is classified according to the battery producer headquarters.

Source: IEA (2025), Global EV Outlook 2025.

China continues to dominate the downstream and midstream global EV battery supply chain, but Indonesia is quickly growing its share of nickel mining and refining

Geographical distribution of the global EV and storage lithium-ion battery supply chain, 2024



Notes: Li = lithium; Ni = nickel; Co = cobalt; Mn = manganese; Ph = phosphate; Gr = graphite; Refining: Li = battery-grade lithium chemicals; Ni = nickel final products including nickel sulphate; cobalt = final refined cobalt products including cobalt sulphate; Mn = battery-grade manganese sulphate; Ph = battery-grade phosphoric acid. LFP = lithium iron phosphate; NMC = lithium nickel manganese oxide. LFP and NMC refer to cathode material production and NMC includes all nickel-based cathode material such as nickel cobalt aluminium oxide (NCA). DRC = Democratic Republic of the Congo. Geographical breakdown refers to the country where the production occurs. All stages of the supply chain are based on data for production in 2024 except for cell components, which is based on production capacity in 2024. Graphite refining refers to all battery-grade graphite production.

Source: IEA analysis based on USGS (2025), Mineral commodity summaries, BloombergNEF, EV Volumes and Benchmark Mineral Intelligence.

Battery demand hit 1 TWh, pack prices reached record lows and LFP continues to rise

Global battery demand from EVs and storage surpassed 1 TWh in 2024, a major milestone, with a 30% year-on-year increase. Growth was primarily driven by growth in EV sales with EV battery demand alone reaching 950 GWh. Electric cars remain the largest source of battery demand, being 80% of total EV and storage battery demand. However, electric trucks were the fastest-growing segment, more than doubling in 2024 and reaching 3% of global EV battery demand, primarily driven by electric truck deployment in China. Europe also saw significant electric truck demand growth, increasing by 45% from 2023.

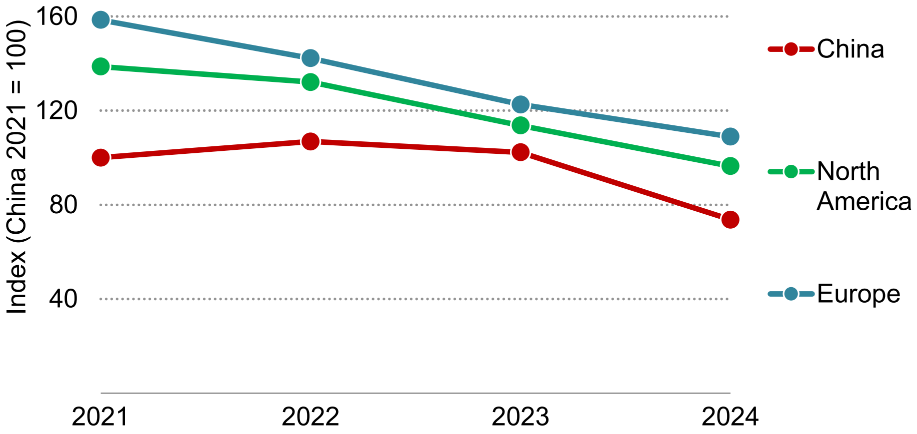
Finally, battery storage demand yet again experienced remarkable growth by around 85% in 2024 after more than doubling in 2023. The majority of the growth was driven by utility-scale deployment. China accounted for half of global storage deployment in 2024, leading the market and almost doubling from 2023. However, the United States saw even higher growth, almost doubling from 2023, with a quarter of global demand. Growth in demand in the United States is strongly driven by California, which accounted for half of the deployment in 2024. Europe saw weaker growth but still accounted for over 10% of demand in 2024. Behind-the-meter storage demand also grew but weaker than utility-scale, though it is more diversified in demand with Europe and China both being 30% of 2024 demand. Battery storage now makes up 15% of the global EV and storage battery market, demonstrating its increasingly important role in driving global battery demand.

China was again the largest source of battery demand, growing by almost 40%. The United States was the second-largest source of battery demand growth, increasing by over 30% year-on-year. In contrast, growth from Europe stalled given the phase-out of electric car subsidies in several major markets, growing by just 20%.

Battery pack price trends

In 2024, average battery pack prices fell by 20% to a record low of USD 115/kWh, the largest annual drop since 2017. This was primarily driven by falling critical minerals prices, with the share of cathode raw materials in the total battery pack price dropping to just over 10% – its lowest level since 2016 – from over 20% in 2023. This indicates that the price reductions of battery critical minerals prices were larger than those of other cost reduction drivers. Other factors contributing to battery pack price declines include ample cell manufacturing capacity, economies of scale, increased adoption of LFP batteries, and intense price competition among battery manufacturers, particularly in China.

Battery pack prices by region, 2021-2024



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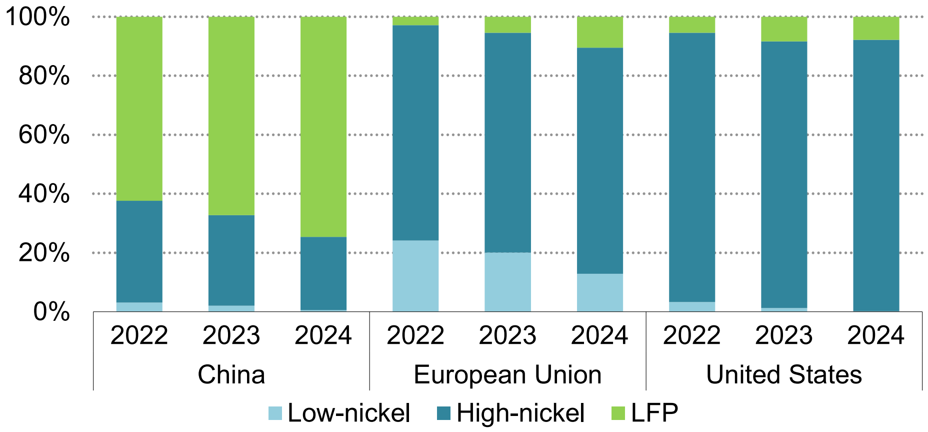
Note: Prices refer to average battery price in the region, including both domestically produced and imported batteries.
Source: IEA analysis based on BloombergNEF.

Battery pack prices fell in all markets, but the extent of price drops varied considerably between regions and countries. In China prices fell around 30% in 2024, compared with just 10-15% in the United States and Europe, increasing the competitive advantage for Chinese battery and EV producers. Considerable excess manufacturing capacity in China has driven fierce price competition among manufacturers, squeezing margins and increasing manufacturing efficiencies and yields as they compete for market share. This has driven down battery manufacturing costs further, also supported by the country's fully integrated battery supply chain and large skilled workforce, enabling a faster pace of cost reductions and innovation over other regions. The widespread use of LFP chemistry in China also contributed to steeper battery price declines in the country. LFP batteries are almost entirely produced in China and are around 30% cheaper per kilowatt-hour than lithium nickel cobalt manganese (NMC) batteries, which remain the predominant batteries used in other regions.

Battery chemistry and innovation trends

In 2024, LFP batteries made up almost half of the global EV battery market. The remarkable resurgence of LFP batteries was initially driven by high nickel and cobalt prices in 2021-2022. However, their continued growth has sustained even as mineral prices have declined, driven by increased competition in the EV market and improved LFP energy density. The pressure to reduce EV production costs and prices in competition for market share has driven OEMs to increasingly utilise LFP batteries. This has been combined with the increasing competitivity of LFP batteries in terms of energy density due to innovations in China such as cell-to-pack batteries, which eliminate dead weight in the battery pack or remove the pack entirely. LFP deployment is led by China, meeting three-quarters of the domestic EV market. In the European Union, the share of LFP almost doubled to reach over 10% of the domestic EV market. In the United States, the LFP share contracted slightly in 2024, remaining below 10%.

Electric vehicle cathode chemistry sales share, 2022-2024



Notes: Low-nickel includes NMC333, NMC432 and NMC532 (NMC = lithium nickel manganese cobalt oxide). High-nickel includes: NMC622, NMC721, NMC811, nickel cobalt aluminium oxide (NCA) and nickel manganese cobalt aluminium oxide (NMCA). LFP includes LFP and lithium iron manganese phosphate (LMFP). Sales share is based on capacity. Two-/three-wheelers are excluded from the analysis.
Source: IEA (2025), Global EV Outlook 2025.

Beyond increasing the energy density of LFP, there has also been the introduction of fast-charging LFP batteries, first pioneered by CATL in 2023 with its Shenxing battery. In 2024 CATL took this further and unveiled its Shenxing PLUS LFP battery, which can achieve a 1 000 kilometre (km) range as well as a 15-minute full charge, taking the competitiveness of LFP batteries a step further. BYD pushed fast charging even further with the announcement of its six-minute full charge battery in March 2025, capable of delivering 400 km range in five minutes. BYD simultaneously launched its own 1 megawatt charging platform capable of charging at these speeds and integrating battery storage to mitigate peak demand effects and optimise grid loads. BYD plans widespread roll-out of its new platform. CATL overtook BYD in April 2025 further announcing their newest Shenxing battery could deliver 520km range from just 5 minutes charging. The limitation to fast charging now rests on high-power charger availability more than battery limitations.

Sodium-ion batteries have experienced waves of development attention based on the prevailing lithium prices. The economic advantages of sodium-ion batteries are most apparent in high lithium price environments; however, lithium prices have fallen since 2023 and remained low throughout 2024. A recent study suggests that unless sodium-ion batteries achieve significant improvements in energy density or lithium prices rise substantially again, it may be challenging for sodium-ion batteries to compete with LFP on cost. Nevertheless, the superior low-temperature performance of sodium-ion compared with LFP is still driving its development. In 2024 CATL launched its new Freevoy Super Hybrid battery, which contains both sodium- and lithium-ion cells, with the sodium-ion cells enabling operation in temperatures as low as -40 °C. CATL also announced its second generation sodium-ion cells in April 2025 with higher energy density under a new brand, Naxtra. BYD started construction of its first sodium-ion battery plant in 2024 for both EVs and storage applications. HiNa also released its new sodium-ion battery, presenting higher energy density and faster charging.

Progress was also made in solid-state batteries with large prototypes and investments from Samsung SDI, CATL, Toyota, Quantumscape and others. Though several companies are aiming for mass production as early as 2027-2028, solid-state batteries remain at large pilot stage and are yet to demonstrate superior performance at commercial scale. Some companies are utilising a hybrid solid-liquid electrolyte which could negate some safety advantages over conventional lithium-ion batteries if still a flammable organic liquid. Scaling production, reducing defect rates and achieving competitive costs at scale remain key barriers to the widespread deployment of solid-state batteries.

Manganese-rich chemistries are another significant chemistry shift that is already having impact. Manganese is already being utilised in the higher-energy-density variant of LFP, lithium manganese iron phosphate (LMFP), which was deployed in six commercial EV models in China in 2024. There is also a push towards lithium and manganese-rich nickel manganese cobalt oxide (NMC) chemistries, enabling lower costs by reducing nickel and cobalt content, while delivering higher energy densities than LFP and LMFP. For instance, Umicore is targeting commercial production of its manganese-rich cathodes for EVs by 2026. Lithium nickel manganese oxide (LNMO) is another manganese-rich chemistry which contains no cobalt and is under development. Though manganese-rich chemistries reduce pressure on nickel and cobalt mineral supplies, there is a concurrent increase in battery-grade manganese sulphate supply chains (see Chapter 2).

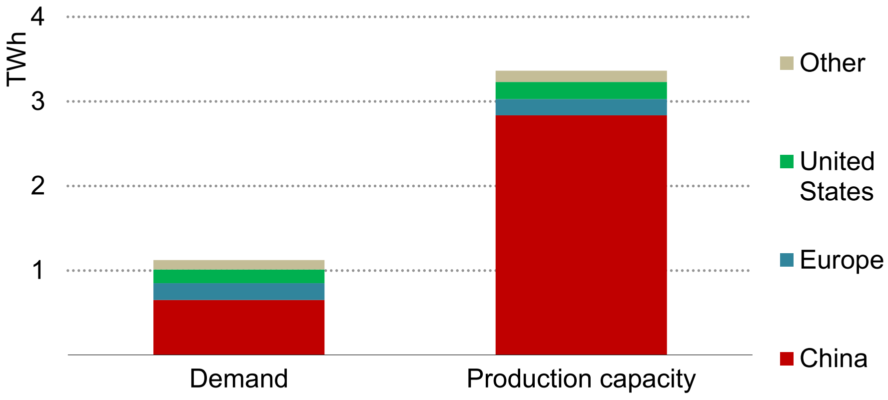
Despite the novel chemistries, the primary driver of battery innovation remains with conventional chemistries. Novel cell formats, pack designs, cell integration into the chassis or car body (cell-to-chassis/cell-to-body), “no-degradation” batteries and faster charging versions of both LFP and nickel-based chemistries are being consistently developed. The wider application of artificial intelligence (AI) in battery research and manufacturing is also notable – AI is already being used for image-based defect analysis on leading manufacturing lines today.

Battery manufacturing trends

Global battery cell manufacturing capacity grew 30% in 2024 to reach more than 3 TWh, around three times the total EV and storage battery cell demand the same year. The battery manufacturing market is maturing and entering a period of consolidation and intense competition.

Around 85% of global manufacturing capacity is in China. Battery production capacity grew by almost 50% in the United States in 2024, surpassing that in the European Union, which grew by 10%. The Inflation Reduction Act (IRA) has rapidly increased investment in battery production capacity in the United States, and if all announced projects come online, the United States is set to have over 1.2 TWh of production capacity by 2030, up from 220 GWh in 2024.

Battery demand and production capacity, 2024



IEA. CC BY 4.0.

Note: Capacity shows nameplate capacity.
Source: IEA analysis based on Benchmark Minerals Intelligence.

Korean battery producers remain the largest players overseas with over 400 GWh globally, compared with just 60 GWh for Japanese companies and 30 GWh for Chinese companies. In 2024, Korean companies such as LG Energy Solution, Samsung SDI and SK On owned almost 85% of battery production capacity in the European Union and 40% in the United States. However, the share of production capacity in the European Union owned by Korean companies is set to drop to just 30% in 2030 with significant announcements from Chinese- and European-owned battery producers, although for new players, achieving successful scale-up of production at competitive prices may be challenging.

The European battery industry faced considerable challenges in 2024. The leading homegrown battery producer, Northvolt, filed for bankruptcy in Sweden. This was driven by serious challenges in scaling battery cell production, in particular an inability to sufficiently reduce the defect rate. These challenges were exacerbated by trying to scale production of several stages of the supply chain simultaneously. The Northvolt case provides a reminder of the significant complexities and challenges of scaling high-quality battery cell production for new players.

Battery recycling

Global battery recycling capacity is dominated by China with over 80% of global capacity for both pretreatment and material recovery stages. Manufacturing scrap is the dominant feedstock, anticipated to account for two-thirds of recyclable material in 2030, until EVs reach end-of-life at scale. Therefore, battery recycling facilities tend to be planned next to battery manufacturing facilities to minimise transportation costs of manufacturing scrap. There is currently significant competition for black mass (the primary battery recycling feedstock) due to significant excess recycling capacity in China, which was five times larger than domestic feedstock availability in 2023. In 2025 the European Commission classified black mass as hazardous waste to restrict unmanaged export to non-member countries of the Organisation for Economic Co-operation and Development under the Waste Shipments Regulation, a move aimed to retain black mass feedstock in the region, ensure it is recycled sustainably, and de-risk domestic recycling projects by avoiding direct competition with Chinese battery recyclers for black mass, thus supporting the development of a European battery recycling industry.

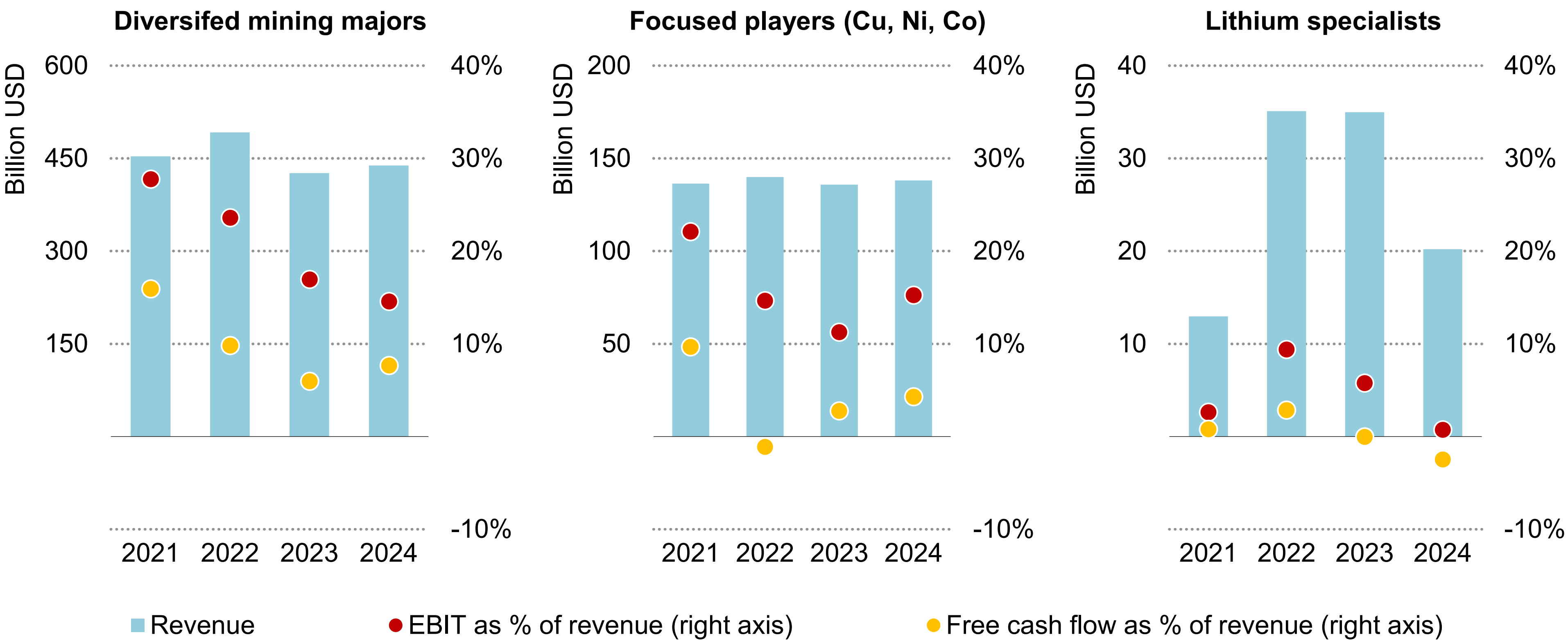
Global battery supply chain

China retained its dominance over the midstream and downstream EV and storage battery supply chain in 2024, processing 70-95% of global lithium, cobalt, phosphate and graphite; producing 98% of LFP cathode material, two-thirds of nickel-based cathode material, over 90% of anode material and 80% of global battery cells. Indonesia has increased its share of upstream nickel production, supplying 60% of nickel mined supply and processing almost 45%. In Chapter 3 we explore the NMC, LFP and sodium-ion battery supply chains in detail in the battery supply chain deep dive.

Investment trends

Ongoing price declines have strained producers' financial performance, with particularly severe impacts on lithium producers

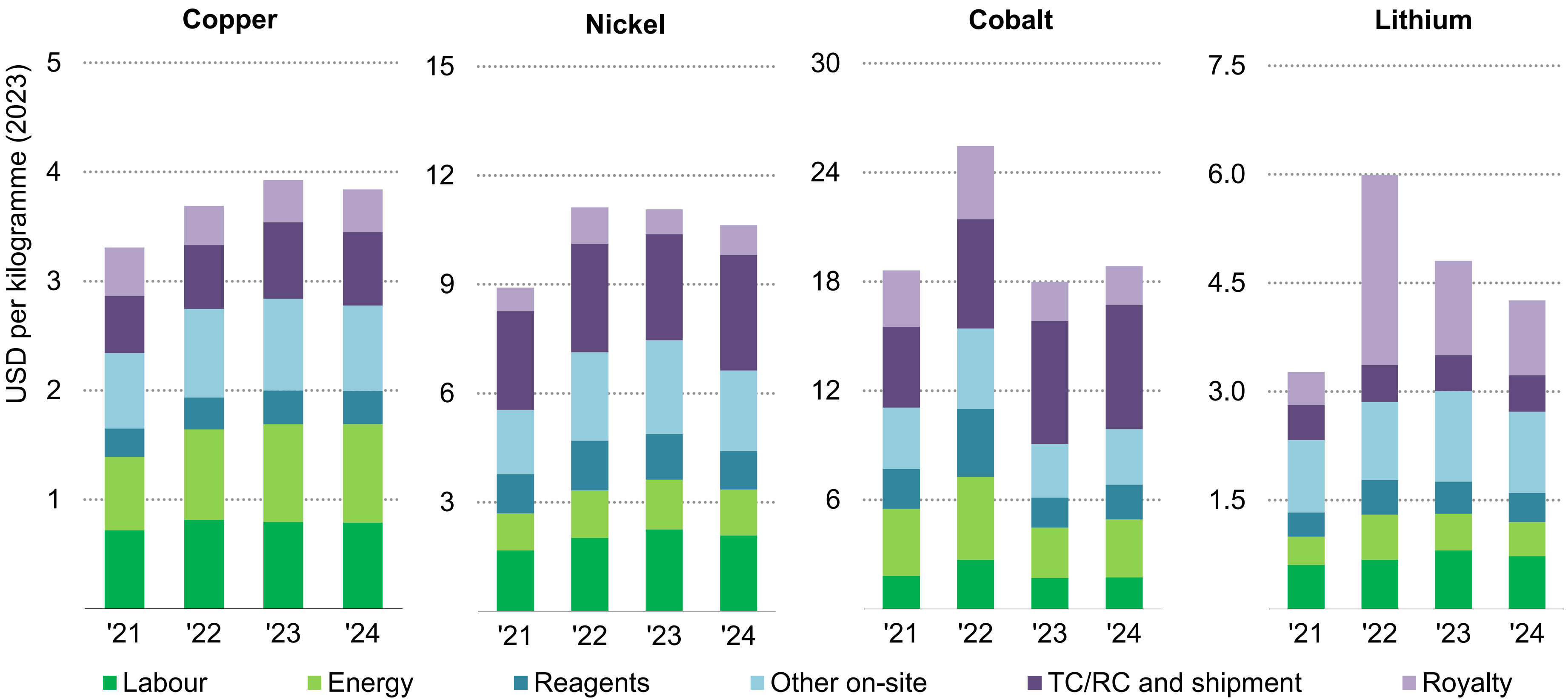
Aggregate financial performance of major mining companies by type



Notes: Cu = copper; Ni = nickel; Co = cobalt; EBIT = earnings before interest and taxes.
Source: IEA analysis based on S&P Global.

In 2024, production costs for lithium, nickel and copper exhibited a modest decline

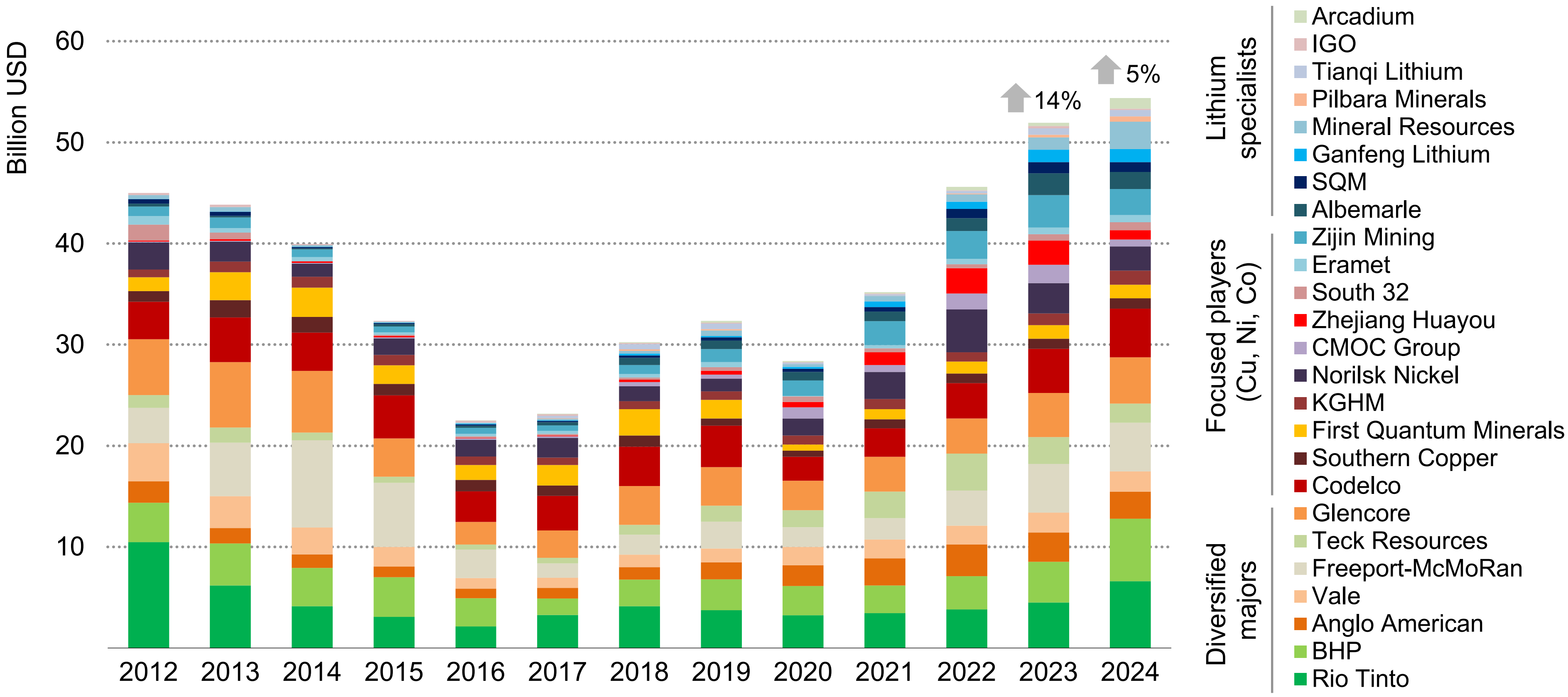
Production cash cost trends



Notes: TC/RC = treatment and refining charges. Production cost is based on the weighted average value for the assets in the 75th quartile.
Source: IEA analysis based on S&P Global.

Growth in critical mineral investment slowed in 2024, with the impact varying by company type

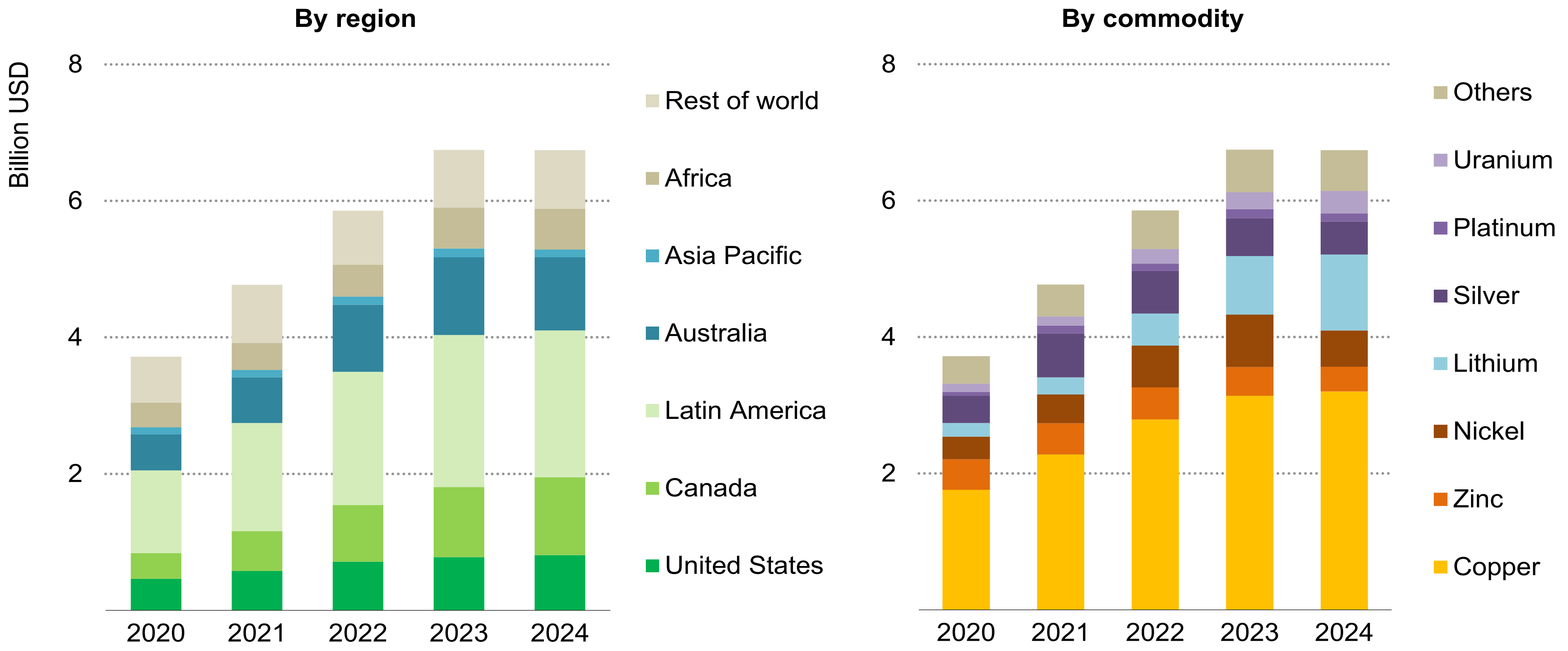
Capital expenditure on non-ferrous metal production by major mining companies



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 S&P Global.

Exploration spending in 2024 was similar to levels in 2023, marking a pause in the strong growth trend that has been seen since 2020

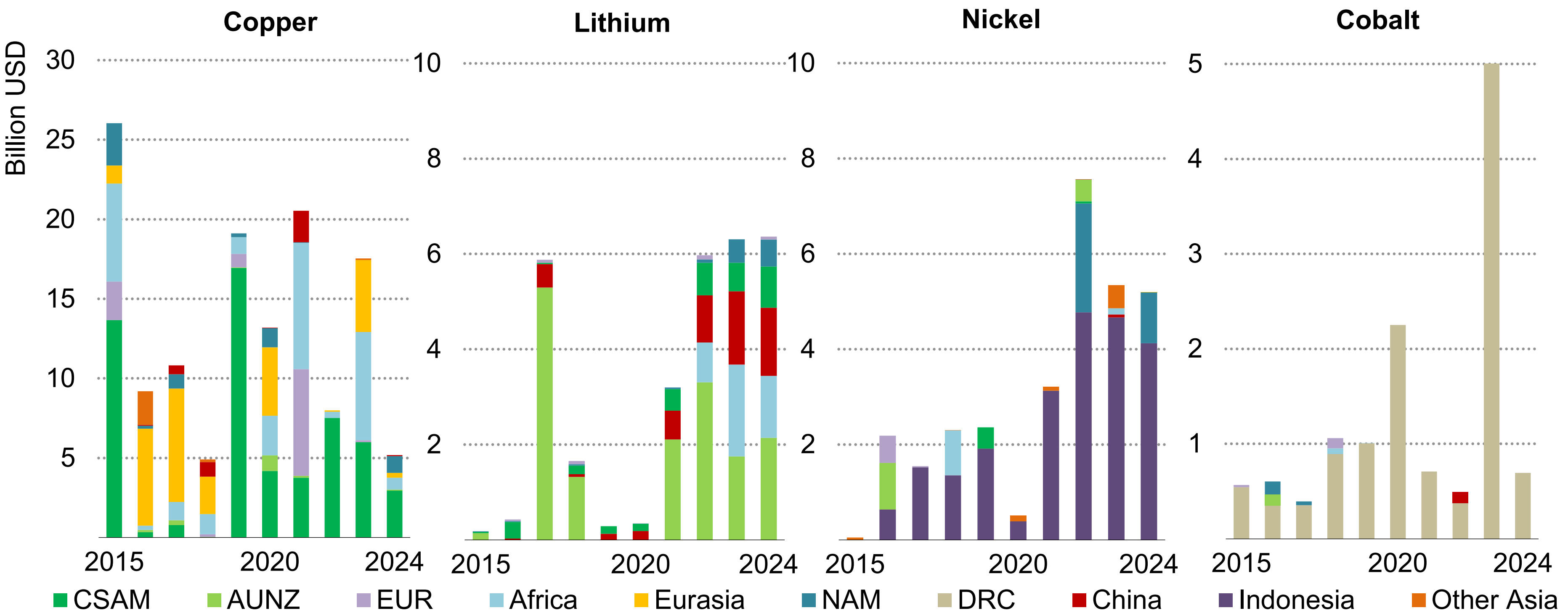
Exploration spending for selected nonferrous mineral resources



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

Investment trends vary by region, with Central and South America seeing the largest overnight greenfield mining investment levels, followed by Indonesia and Africa

Overnight greenfield mining investment for key energy minerals, 2015 to 2024

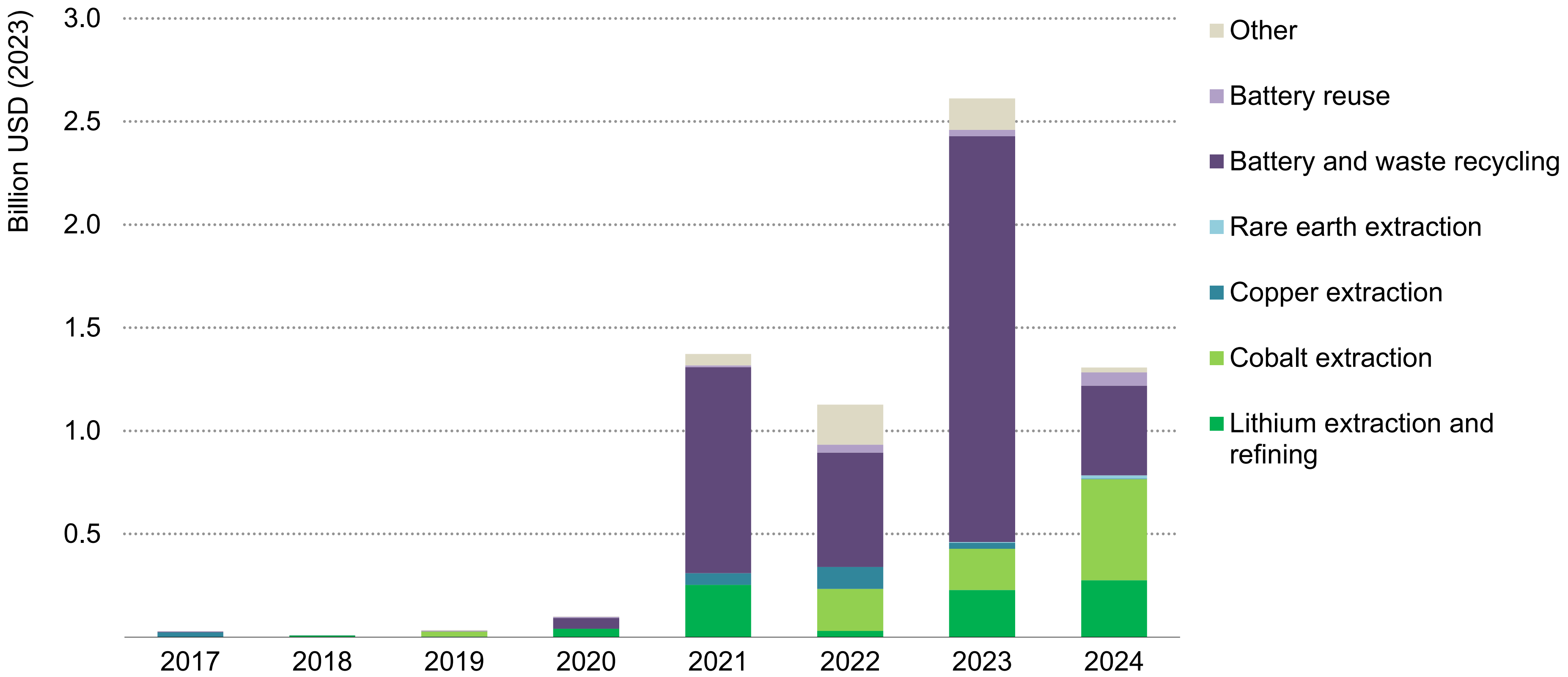


Notes: CSAM = Central and South America; AUNZ = Australia and New Zealand; NAM = North America; DRC = Democratic Republic of the Congo. Considers only overnight greenfield investment, which are calculated based on capital intensities by region in 2024 dollars, collected from S&P and company reports, applied to production additions.

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

Critical minerals continued to attract venture capital investment with new lithium extraction methods and battery recycling remaining the primary focus areas

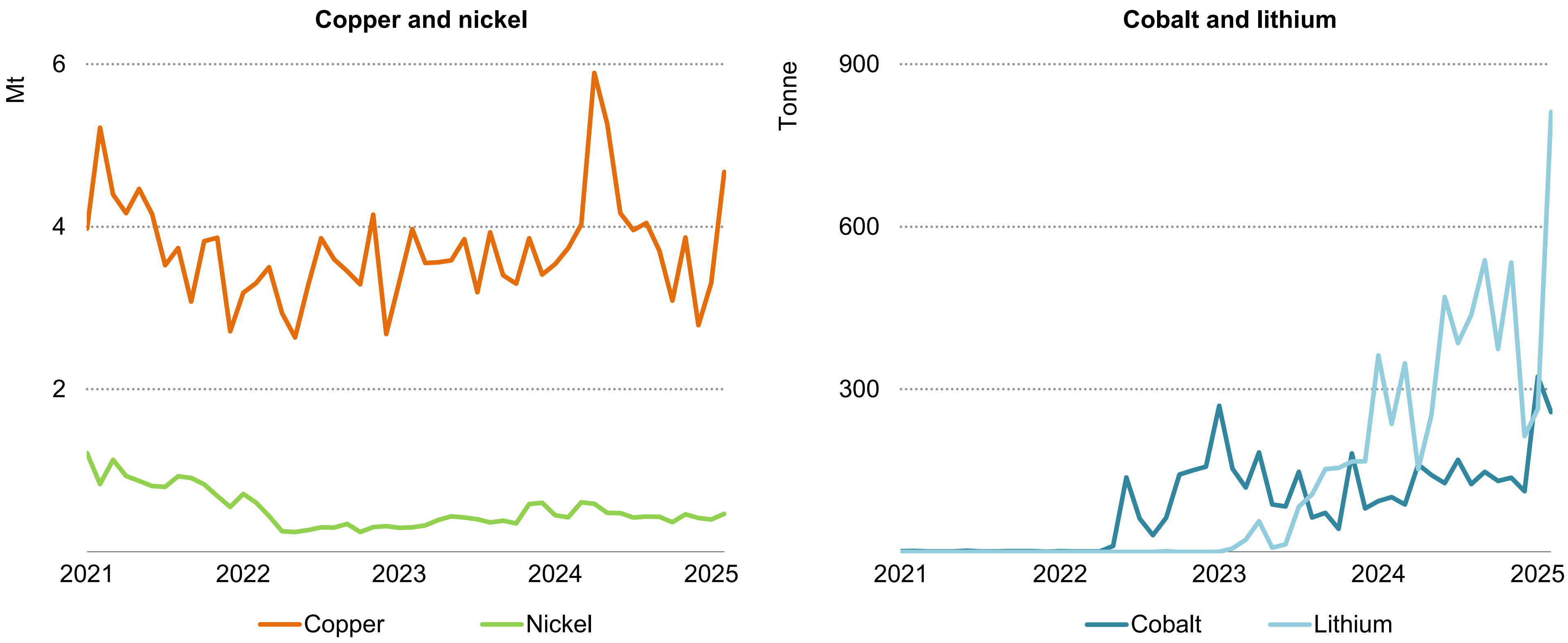
Early- and growth-stage venture capital investment into critical mineral start-ups



Source: IEA analysis based on Cleantech Group i3 database.

Trading volumes for copper fluctuated, nickel was stable, and cobalt and lithium rapidly expanded

Daily trade volume for copper and battery metals at major markets



Notes: Trading liquidity indicates monthly average of daily traded volumes in major metal exchanges. Copper (LME, Shanghai Futures Exchange [SHFE], Chicago Mercantile Exchange [CME]); nickel (LME, SHFE); cobalt (LME, CME); lithium (LME, CME). Trading volumes for cobalt and lithium make up less than 1% of annual production.

Source: IEA analysis based on Bloomberg.

Challenging market environments led to subdued financial performance and investment levels

Industry's financial performance

The sustained low-price environment meant that industry revenues, which had declined by around 10% in 2023, remained roughly at the same level in 2024. Overall, the decline in battery mineral prices combined with increases in prices for some minerals led to a slight year-over-year increase in revenue for diversified mining majors. Free cash flow as a share of revenue also rose marginally from 6% in 2023 to 8% in 2024. The operating profit ratio of companies specialising in copper, nickel and cobalt fared better with a slight recovery from 2023. However, lithium specialists experienced a sharp drop in revenue by over 40% compared with 2023 due to the continued decline in lithium prices; their operating profit ratio fell to around 1% of revenue, while their free cash flow ratio turned negative.

Production cost

The production costs for copper, lithium, nickel and cobalt all increased in 2022 but fell back again for lithium, nickel and cobalt in 2023. Copper was an exception where higher energy costs pushed up production costs. In 2024, production costs for lithium, nickel and copper declined, whereas the production cost for cobalt saw a marginal increase. Meanwhile, fluctuations in royalty payments had the greatest impact on cost trends for lithium, while treatment and refining charges (TC/RC) and shipment played a role for nickel.

Investment spending

Ongoing price declines have strained producers' financial capacity for investment. Our assessment of 25 large mining companies suggests that investment in critical minerals mining grew by 5% in 2024, down from 14% growth in 2023 (excluding iron ore, gold and coal). Adjusted for cost inflation, real investment growth in 2024 was just 2%. However, trends varied by company. Diversified mining majors increased capital spending by around 15%, while specialist players scaled back investment by 15%. Companies focused on lithium development increased investment by around 20%, although this was lower than the around 60% increase seen in 2023. Notably, while major Chinese mining companies had witnessed continuous growth in investments since 2015, this trend was reversed in 2024 with their capital spending declining by 35%.

Overnight greenfield mining investment has increased significantly in the last decade, with investment in the 2020 to 2024 period being 50% higher than the level seen from 2015 to 2020. These trends vary by region. Central and South America attracted the largest share with almost USD 60 billion, largely driven by copper mining. Indonesia and Africa also saw substantial investment, with almost USD 25 billion directed towards nickel mining projects and USD 15 billion toward cobalt. For lithium, although both Central and South America and Australia saw similar production volume additions over the past ten years, the largest overnight investment was by far seen in Australia, driven by hard rock mining activities.

Exploration spending

Global exploration spending witnessed a robust annual average growth rate of about 20% between 2020 and 2023, but it flatlined in 2024 at around USD 6.7 billion. While spending in Canada and the United States increased marginally compared with the previous year, it decreased in Australia and Latin America.

Despite a challenging market environment leading to declines in spending for several minerals, spending on exploration for lithium, uranium and copper increased relative to 2023. Notably, lithium exploration spending rose by 30%, surpassing USD 1 billion for the first time. Increasing demand for electricity driven by the expansions in AI data centres has led to rising interest in nuclear power, resulting in a just under 35% rise in uranium exploration expenditures. With growing concerns around a looming supply gap, copper exploration spending also saw a slight increase.

By contrast, exploration spending for nickel, cobalt, zinc, silver, and platinum decreased. Nickel and cobalt declined by more than 30% compared with the previous year, while zinc, silver, and platinum exploration fell by 10 to 15%. Spending on cobalt and zinc exploration in 2024 was at the lowest level seen over the past five years.

Venture capital spending

Critical minerals have recently emerged as a major area of interest for venture capital (VC) investments. While the record levels of spending (USD 2.6 billion) seen in 2023 were not reached in 2024, VC spending of over USD 1.3 billion was above 2022 levels. The trends show that there are competing technologies being funded, especially for new lithium extraction methods and battery recycling. Direct lithium extraction (DLE) from geothermal brines has been well funded by VC equity and grants in recent years.

In 2023, as interest rates rose, critical minerals even defied the wider declining trends for VC funding, but then succumbed in 2024. For comparison, total energy-related VC also declined by 23% in 2024. Restricted or more expensive capital presents a challenge for some companies trying to scale up to larger projects. For the recycling industry, this problem is compounded by uncertain times to market for recycling companies in the absence of waste material and clear standards. Some notable deals were made with Redwood Materials (recycling), Kobold Metals (AI for exploration), Ascend Elements (recycling), Tianneng New Materials (recycling) and Cornish Lithium (geothermal DLE).

Trading volumes

Inventories and trading volumes of critical minerals at major metals exchanges provide an indication on the liquidity of these commodities. Copper and nickel have been traded for a long time and more actively in the London Metal Exchange (LME), Shanghai Futures Exchange (SHFE) and Chicago Mercantile Exchange (CME) due to their important levels of demand in industries. Trading volumes for copper and nickel at major metals exchanges in 2024 indicate that these were once again the most liquid among key energy minerals.

Copper volumes at the LME, including both futures and options, surpassed 4 million lots in April 2024, a milestone not achieved since June 2016. In 2024, the liquidity of nickel recovered somewhat, but still remains well below the levels prior to the LME's contract suspension in March 2022.

Cobalt and lithium saw notable growth in trading volumes in the LME and CME over the last two years as their demand trended upwards. Lithium contracts soared last year with increased hedging activity from traders and industry after the prices dropped in 2023. The growing demand for lithium has led market players to hedge against increasing exposure to the volatile commodities market. Nevertheless, the trading liquidity for battery metals still lags significantly behind those of other bulk materials, in spite of recent improvements. Fifteen percent of copper and 14% of nickel are traded over exchange compared with annual production and as it stands, daily traded volume as a share of annual production still stands at less than 1% for lithium and cobalt. For metals not traded over exchange, exchange prices provide an important benchmark by which to negotiate private contracts between buyers and sellers.

Liquidities of natural graphite and rare earth elements are very low compared with major metals such as copper or nickel due to limited transactions at spot markets and varied specifications. A notable issue is the lack of transparency on payabilities for intermediate products.

Box 1.3 China's increasing investment in upstream copper, nickel and lithium projects

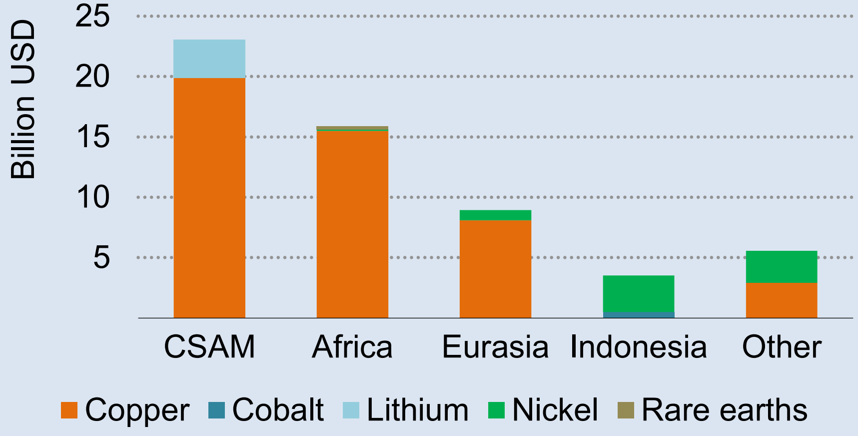
Recently released data from AidData reveals that China channelled nearly USD 57 billion in financial support for key minerals – copper, nickel, lithium, cobalt and rare earth elements – across almost 20 emerging market and developing economies from 2000 to 2021. Notably, approximately 80% of investments targeted copper and copper-cobalt projects, with funding directed to these projects almost every year since 2000. Nickel projects, particularly in Indonesia, received the second-largest financial commitments.

Over time, China has shifted its investment strategy, moving away from a heavy reliance on policy banks (e.g. state-owned financial institutions created to advance national policy goals, such as the China Development Bank) before the pre-Belt and Road Initiative, when these methods accounted for 90% of financing commitments to developing economies. Today, most investment occurs through state-owned commercial banks, such as the Bank of China.

A key part of this shift is the use of a limited recourse project finance model, whereby the lending portfolio supports upstream project companies, including special purpose vehicles (SPVs) and joint ventures (JVs). By providing loans to JVs and SPVs where Chinese companies have equity stakes, China ensures that raw or processed mineral ore produced overseas is directed back to mainland China for further processing.

In these arrangements, mineral output is divided among shareholders based on their equity stakes, set by offtake agreements. This structure not only locks in long-term access to essential ore reserves but also allows China to maintain a level of control over its overseas resource production that full-recourse sovereign debt financing cannot offer.

Chinese investment across primary minerals, 2000-2021

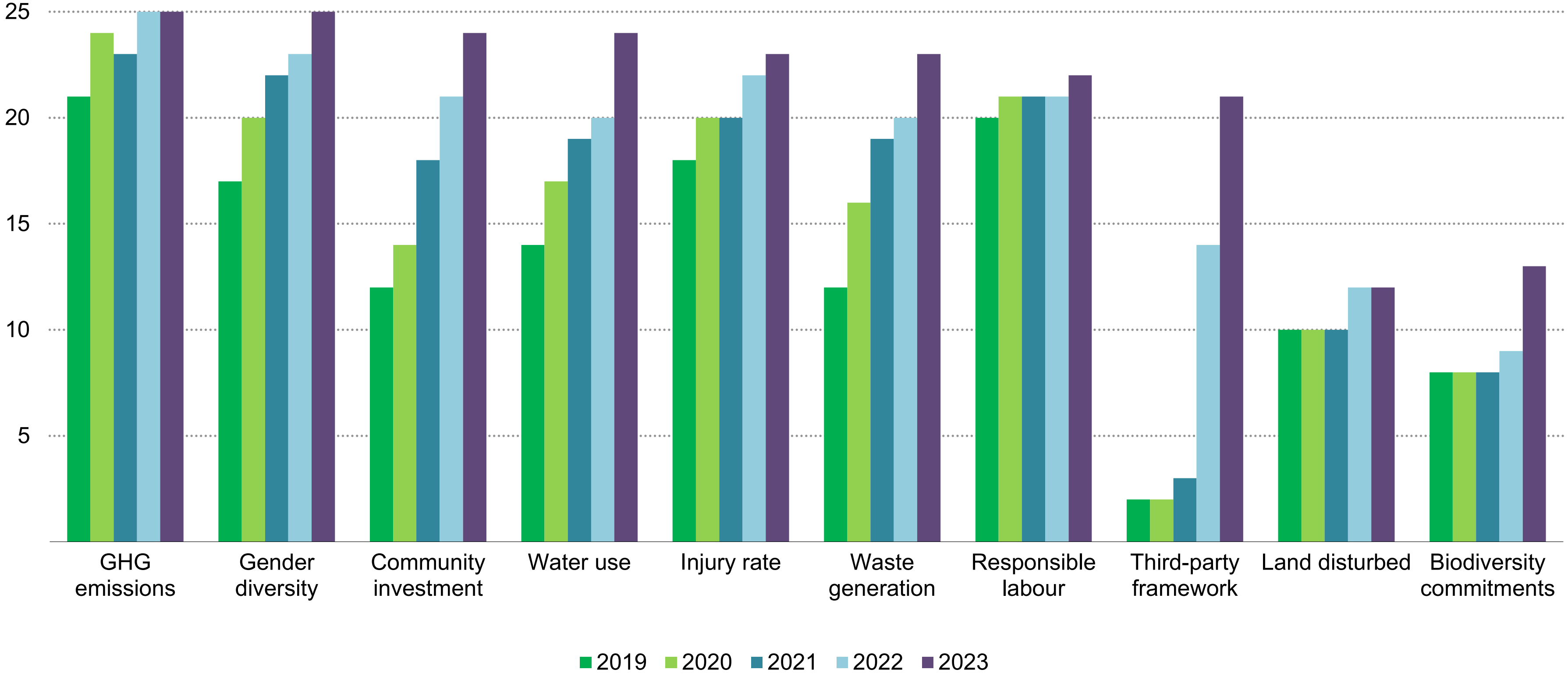


Note: CSAM = Central and South America.
Source: Walsh et al. (2025), Tracking China's Transition Mineral Financing: Methodology and Approach, Version 1.0.

Sustainability performance tracking

Sustainability reporting continues to gain traction across major producers

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



Notes: Greenhouse gas (GHG) emissions refer to reporting on total scope 1 and 2 emissions; gender diversity refers to the share of women in the workforce; water use considers water consumption; responsible labour refers to strategies to prevent child and forced labour; biodiversity commitments refer to companies reporting a target of "no net loss" or "net positive impact". Data from 25 companies were reviewed, so the maximum value for each of the selected indicators is 25.

Sources: 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, NorNickel, Pilbara Minerals, Rio Tinto, South32, Southern Copper, SQM, Teck Resources, Tianqi Lithium, Vale, Zhejiang Huayou, and Zijin Mining Group Co. Ltd.

Companies are recognising that improved performance on sustainability helps mitigate financial risks and ensure compliance

Securing the critical mineral supply chain requires comprehensive consideration of disruption risks. We have identified six priority areas affecting supply security: water, greenhouse gas (GHG) emissions, biodiversity, human rights, communities and corruption.

Our assessment of company progress across various sustainability dimensions – based on the public sustainability reporting of 25 major companies that have a strong presence in critical minerals supply chains – shows progress in public reporting and growing sustainability commitments. Biodiversity commitments increased by over 1.5 times in the past couple of years, with companies pledging that any biodiversity loss will be balanced by conservation efforts to have a net positive effect on biodiversity. Almost twenty companies now have a net zero emissions target, up from fewer than ten in 2019.

Disclosure and third-party verification have also improved. The number of companies reporting the use of third-party frameworks increased more than ten times from 2019 to 2023. Common voluntary standards include those from the International Council on Mining and Metals Principles, followed by Copper Mark, Towards Sustainable Mining and the Initiative for Responsible Mining Assurance. Many Chinese mining companies showed improved disclosure in 2024, with Zijin Mining and CMOC leading disclosure levels in 2024 among the five Chinese companies assessed, while Tianqi Lithium and Ganfeng showed the largest improvements over the last years.

Even though public reporting is improving, sustainability data obtained from that reporting paint a mixed picture, with room for improvement. Gender balance, social investment and safety indicators have improved since 2019, but reporting for 2023 indicates a setback in progress. From 2019 to 2022, gender balance in the senior management improved steadily, with women's representation rising from less than 5% to around 15%. Companies also increased their social investment, which peaked at just over USD 1.2 million per tonne produced. Spending per revenue also saw a notable increase during this period. Meanwhile, injury rates were nearly halved, falling from around 2% to just over 1%. However, data for 2023 shows a decrease in the share of women in senior management, lower social investment levels and higher injury rates.

On the other hand, indicators representing environmental performance such as GHG emissions, water use and mine waste have started to show improvement in 2023. Across all these metrics, companies have become more efficient per unit of output, suggesting progress in operational performance and resource management among larger producers. Declining ore grades make it more challenging to reduce absolute levels of mining waste, emissions and water use, but there are several technologies available to enable further progress.

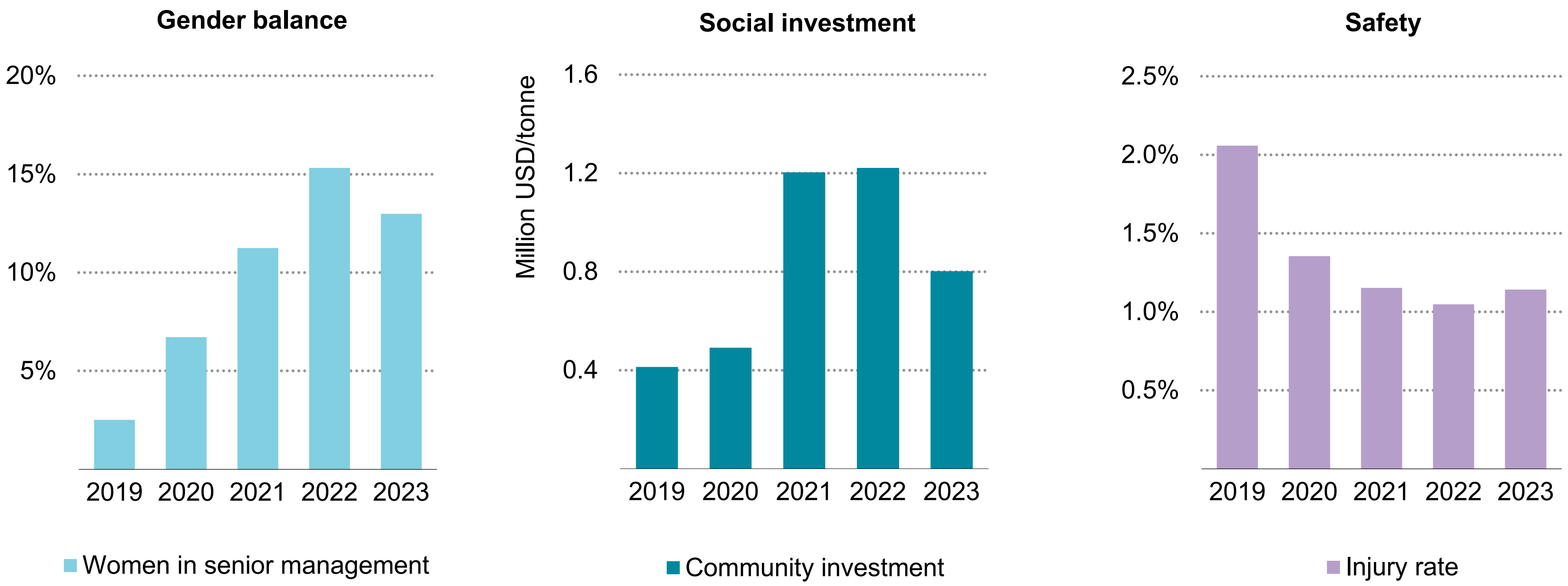
For water intensity, a notable drop in average water consumption after 2019 was maintained throughout 2023, with water consumption per mined output declining between 2019 and 2023. For mining waste, average waste generation has increased overall since 2019, likely reflecting lower ore grades over time. Nevertheless, waste generation per mined output declined in 2023, though this was still higher than in 2019. After years without much change, GHG emissions saw a significant decline in absolute scope 1 and 2 emissions per mined output in 2023.

GHG emissions performance can vary significantly by mineral and whether mining or refining is being considered. Data from Skarn Associates reveals that GHG emissions intensities for some minerals, such as copper, saw large improvements from 2019 to 2024. For copper, this is almost entirely driven by reductions in scope 2 emissions resulting from the utilisation of Power Purchase Agreements, with scope 1 emissions falling only marginally. Nickel, similarly, has seen improvements, though it still has the absolute highest intensities at 44 tonnes of CO_2-equivalent (t CO_2-eq) per tonne of nickel produced for mining and 47 t CO_2-eq per tonne of nickel produced for refining, five times higher than the second-most emissions-intensive mineral (cobalt for mining and lithium for refining). Lithium had an overall increase in GHG emissions intensities largely due to a shift in production towards hard rock in Argentina and Chile; lithium produced from hard rock generally has higher GHG emissions intensities.

Despite progress in reporting of and performance in sustainability metrics over time, there has started to be some pushback on regulations that require transparency and due diligence on sustainability matters. For example, in the European Union, there has been corporate criticism of excessive regulation, linking this in turn to reduced EU competitiveness. This led the European Commission to propose an omnibus package that aims to streamline sustainability requirements, including those contained in the Corporate Sustainability Reporting Directive and the Corporate Sustainability Due Diligence Directive. In the United States, the Securities and Exchange Commission paused the adoption of its 2024 climate-related disclosure rules, while a bill has been introduced in Congress to prohibit certain US companies from complying with foreign sustainability due diligence regulations.

Progress in gender balance, social investment and safety indicators had a setback in 2023…

Performance of the top 25 mining companies on share of women in senior management, community investment and injury rate

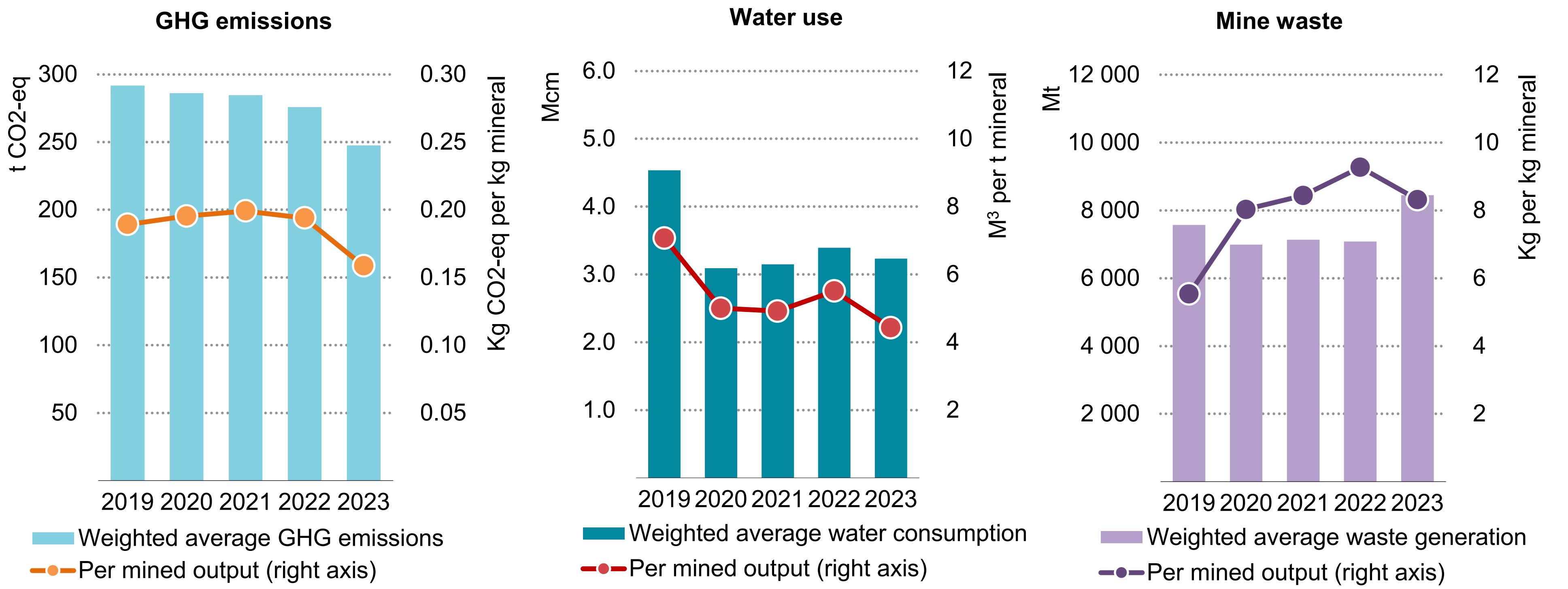


Note: Shows weighted averages by production, except for the share of women in the senior management, which is weighted by the total number of employees. Social investment refers to a company's reported community investment in USD million often measured in terms of the amount of money invested in community projects and initiatives by companies; and safety refers to the total recordable injury frequency rate reflecting the number of fatalities, lost time injuries, substitute work and injuries requiring treatment by a medical professional per 200 000 hours worked.

Sources: 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, NorNickel, Pilbara Minerals, Rio Tinto, South32, Southern Copper, SQM, Teck Resources, Tianqi Lithium, Vale, Zhejiang Huayou, and Zijin Mining Group Co. Ltd.

… but environmental indicators started to show improvements

Performance of the top 25 mining companies on average GHG emissions, water use and hazardous waste

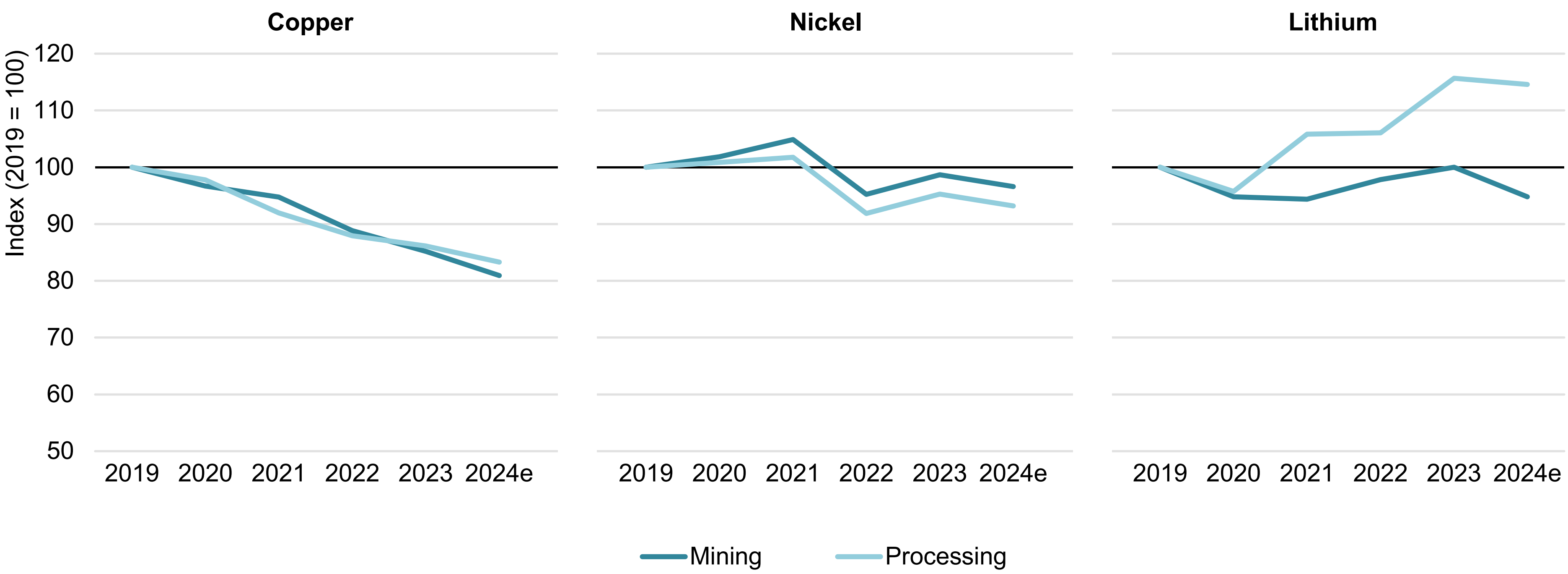


Notes: kg = kilogrammes; mcm = million cubic metres; M^3 = cubic metres; t = tonne. GHG emissions refers to greenhouse gas emissions per mined output (kilogrammes of CO_2 equivalent per kg mineral); water use refers to water consumption per mined output (cubic metre/tonne of mineral); and hazardous waste refers to the waste generated per mined output (kg/mineral).

Sources: 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, NorNickel, Pilbara Minerals, Rio Tinto, South32, Southern Copper, SQM, Teck Resources, Tianqi Lithium, Vale, Zhejiang Huayou, and Zijin Mining Group Co. Ltd.

Progress in emissions intensities varies by mineral, with copper and nickel having seen declines in overall emissions intensity and lithium an increase in intensities from the processing stage

Change in GHG emissions intensities, 2019 to 2024e



Notes: 2024e = estimated values for 2024. Mining covers scope 1 and 2 GHG emissions intensity (measured in tonnes of CO_2-equivalent per tonne of mineral). Processing covers scope 1, 2 and 3 GHG emissions intensities, usually up to refined metal or first saleable product.
Source: IEA analysis based on the data provided by Skarn Associates.

Critical mineral supply disruptions caused by environmental, social and governance factors show the need for continued monitoring and mitigation of related risks to ensure secure supplies

In 2024, mineral production across numerous regions encountered heightened environmental, social and governance (ESG) risks amid regional conflicts and a changing climate. These can put critical mineral supply chains at risk as they could limit market access, create legal barriers, discourage investment, damage company reputation, increase the likelihood of opposition from local communities and other stakeholders, and physically prevent mines and processing facilities from operating.

For example, water scarcity, including in Latin America's lithium triangle, presents a major issue, as over 50% of current lithium and copper production occurs in areas of high water stress. This can cause disruptions to global copper supply; according to data from Skarn Associates, almost 7% of global copper supply is at risk of disruption from floods or droughts in 2024, which is set to increase by 30% by 2030, putting almost 2 Mt at risk. Central and South America faces the highest levels of risk, with almost 10% of its production at risk, but both North America and Asia face increasing risks as well.

In some cases, these issues have fuelled environmental and social opposition. In March 2024, a provincial Argentinian court ordered a pause to new permits for mining around the Los Patos River pending a comprehensive environmental impact assessment, citing environmental appeals filed by local communities.

Conflict associated with mineral production has dampened international investment into mineral supply chains and infrastructure on more than one occasion. In Indonesia, European companies BASF and Eramet withdrew from a USD 2.6 billion planned nickel and cobalt refinery after reports of negative human and environmental impacts associated with the surrounding nickel mining operations, although neither company expressly cited these controversies as a reason for withdrawing. In February 2025, the European Union suspended the EU-Rwanda Memorandum of Understanding on Sustainable Commodity Value Chains following Rwandan forces' occupation of mineral-rich territories on the border between Rwanda and the Democratic Republic of the Congo.

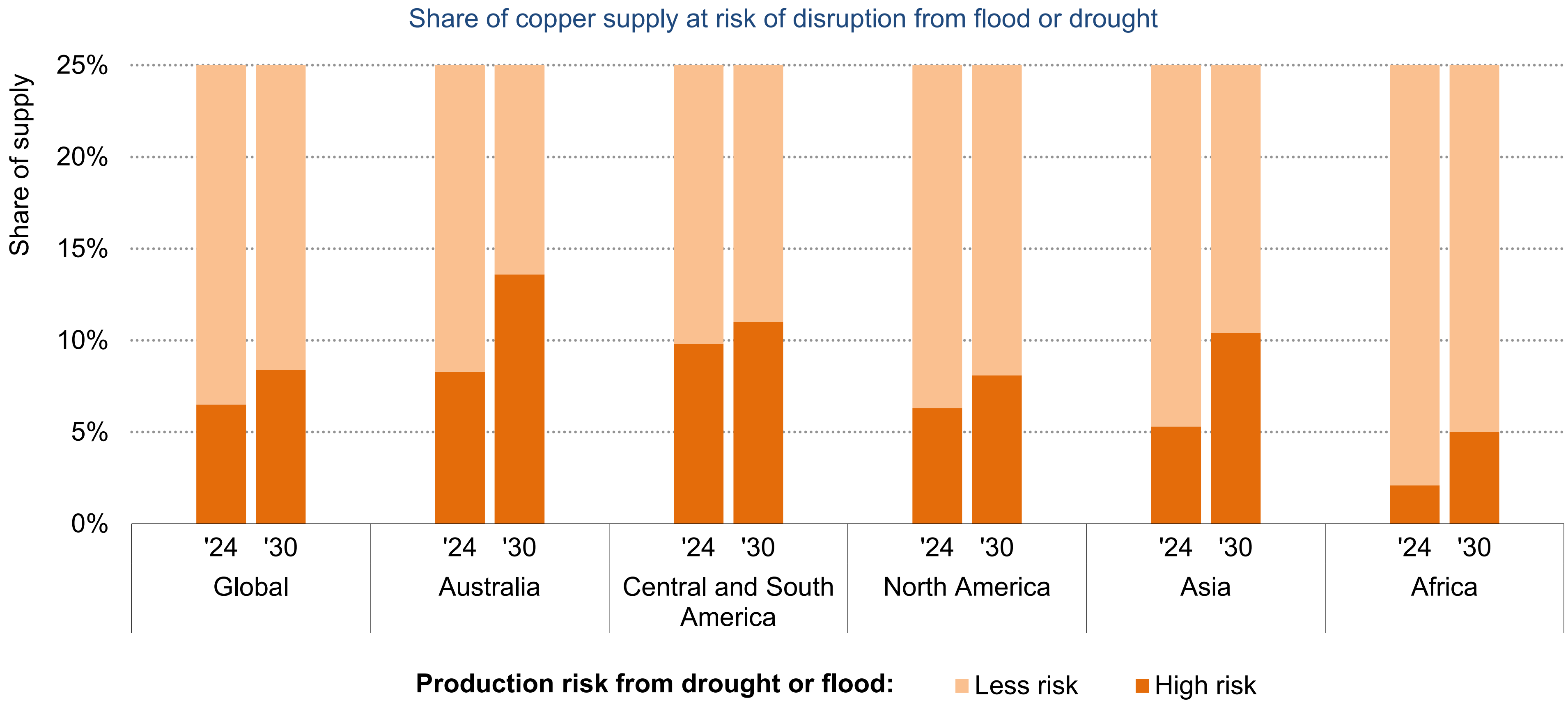
Conflicts have also directly affected critical mineral operations as well as key purchasers. In October 2024, the Kachin Independence Army seized the town of Panwa, Myanmar, a major rare earth production site, disrupting rare earth supply chains. In December 2024, the Democratic Republic of the Congo filed criminal complaints against

Apple subsidiaries in France and Belgium for using conflict minerals in their supply chains. Also in 2024, tungsten prices rose due to a supply disruption in China driven by production cuts and stricter environmental regulations in mining areas. This supply tightness was exacerbated by regional military conflicts amid robust demand from the photovoltaic, EV manufacturing and other industries.

These events highlight the benefits of improving sustainability performance in the long run. Responsible practices across the value chain help to avoid supply disruptions and prevent financial and reputational risks. For instance, Buenaventura signed a water concession with the Peruvian government and is negotiating an agreement with local communities to ensure local buy-in for the Algarrobo copper mine in Peru. In this region, long delays in mining operations due to local opposition are common. BHP's Olympic Dam operation in Australia – an integrated mining and processing facility handling copper, gold and uranium – established agreements worth over AUD 156 million with Indigenous suppliers. This provides employment opportunities and facilitates community development, while contributing to the overall success and sustainability of the operation.

Transparency is key to mitigating supply chain risks while demonstrating compliance with regulations and investor goals. Effective traceability systems (see box 1.4) enable better data collection and tracking of the sustainability performance of specific products. Many companies have already adopted the GRI 14: Sector Standard for Mining ahead of its coming into force in January 2026. Companies also use industry-specific standards, such as the Sustainability Accounting Standards Board (SASB), to highlight sustainability risks and opportunities that are financially material or particularly important to investors.

Copper supply at risk of disruption from droughts or floods is set to increase between 2024 and 2030



Note: Data covers 84% of global copper supply in 2024.
Source: IEA analysis based on Skarn Associates.

Box 1.4 Role of traceability in supporting policy goals in critical mineral supply chains

Traceability systems can help meet various policy goals for critical minerals, including contributing to the development of sustainable, responsible and secure critical mineral supply chains. Traceability systems can act as a tool to obtain data on a product's origin, geographical path, ownership (chain of custody) and physical evolution. In addition to these information elements, traceability systems can also be used to obtain sustainability data on specific products (provided these data are integrated into traceability systems), for example data on GHG emissions along the supply chain.

Tracking this information along the supply chain can allow companies to achieve several objectives, including product differentiation, compliance with regulatory requirements (e.g. market access limitations), and attainment of incentive targets. It may also enable pricing differentiation and help companies identify potential reputational risks within their supply chains.

By enabling companies to achieve these objectives, traceability can, in turn, allow governments to achieve their own policy objectives, including supply chain diversification, national and economic industrialisation goals, building sustainable and responsible supply chains, as well as other policy objectives (e.g. product safety, national security and trade sanctions).

Despite the potential, traceability systems must be thoughtfully designed to balance added value, robustness and practicality while maintaining credibility at a reasonable and proportionate cost. Reliable and standardised data input, along with an interoperable technical infrastructure, is essential for an effective traceability system. Collaboration across the supply chain is also critical for data verification, involving civil society, industry associations and sustainability initiatives. Moreover, system design must take into account the unique characteristics and risk profiles of each commodity, including geographical concentration, supply chain complexity, number of players and the nature of associated risks.

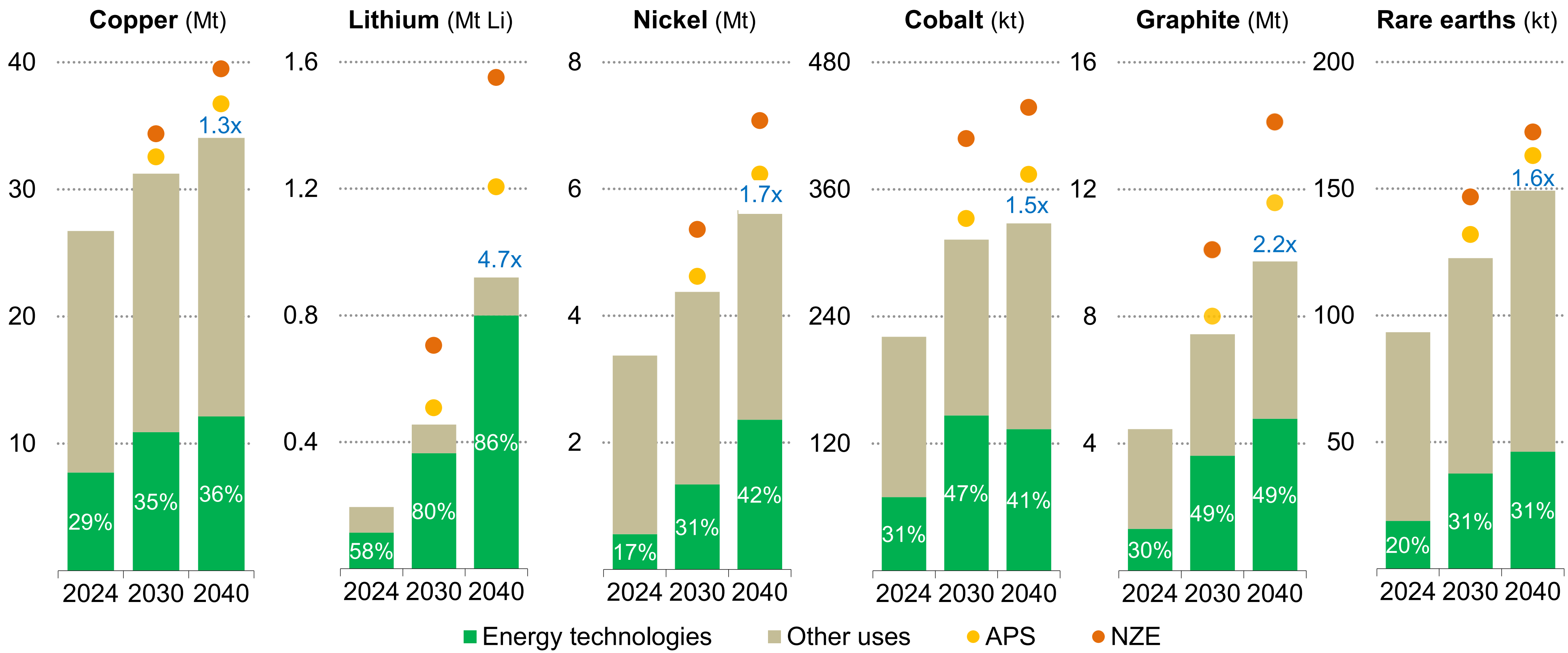
To enhance effective mineral traceability, governments have various tools at their disposal, including: promoting the development and use of interoperability protocols; providing financial support for the development of technical infrastructure for traceability; establishing trust mechanisms to certify the origin of minerals or operator's compliance with legal requirements (e.g. through verifiable credentials); creating incentives for downstream actors to increase traceability, including economic incentives (such as tax credits) and regulatory requirements (such as due diligence requirements and trade measures); and engaging with stakeholders in foreign jurisdictions to foster collaboration and data-sharing across borders.

2. Outlook for key minerals

Outlook overview

Demand for critical minerals continues to rise across all scenarios, driven by the rapid deployment of energy technologies

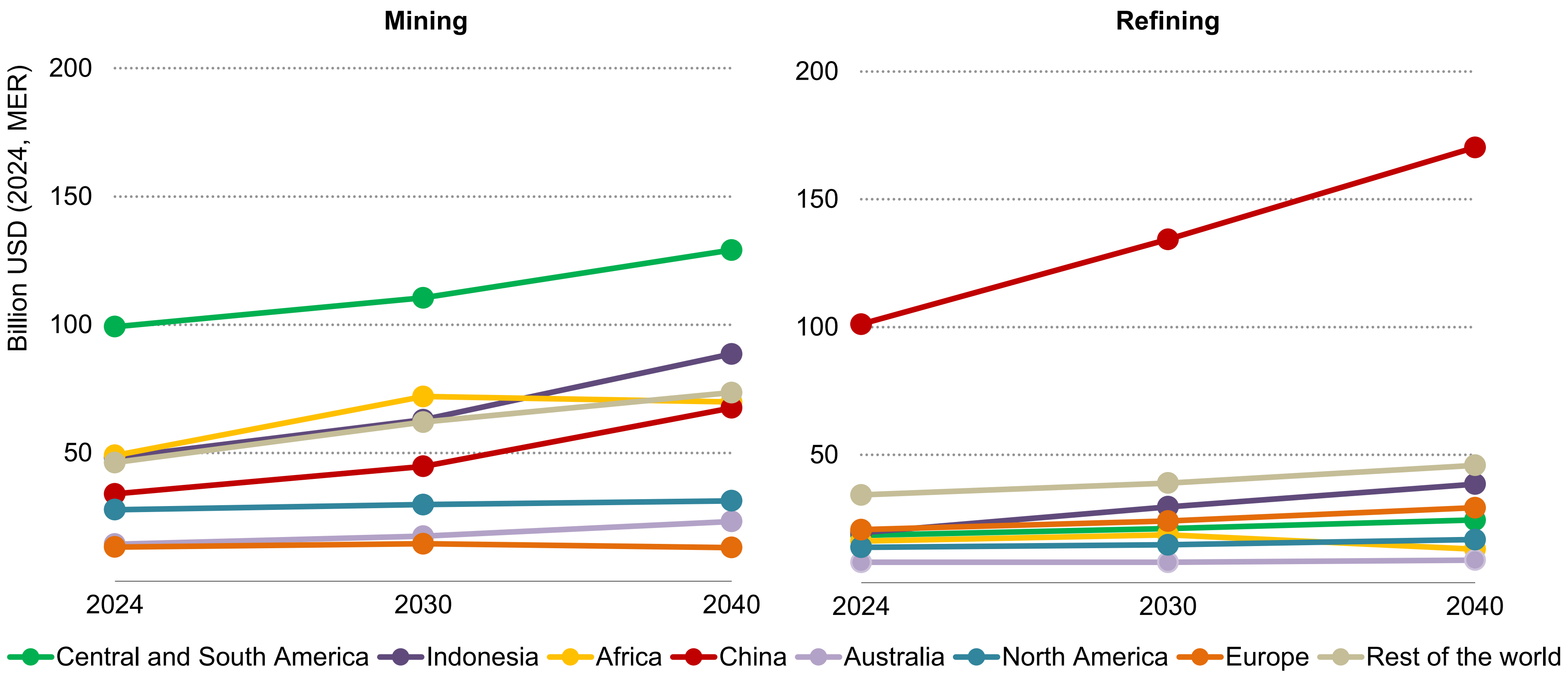
Global critical minerals demand in the STEPS



Notes: STEPS = Stated Policies Scenario; Mt = million tonnes; kt = kilotonnes; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. The figures for copper are based on refined copper (excluding direct-use scrap). Those for rare earth elements are for magnet rare earth elements only. Growth rates (in blue) are between 2024 and 2040.

A growing number of planned projects indicate a 1.5-fold increase in the market value of mineral production by 2040, led by Latin America for mining and China for refining

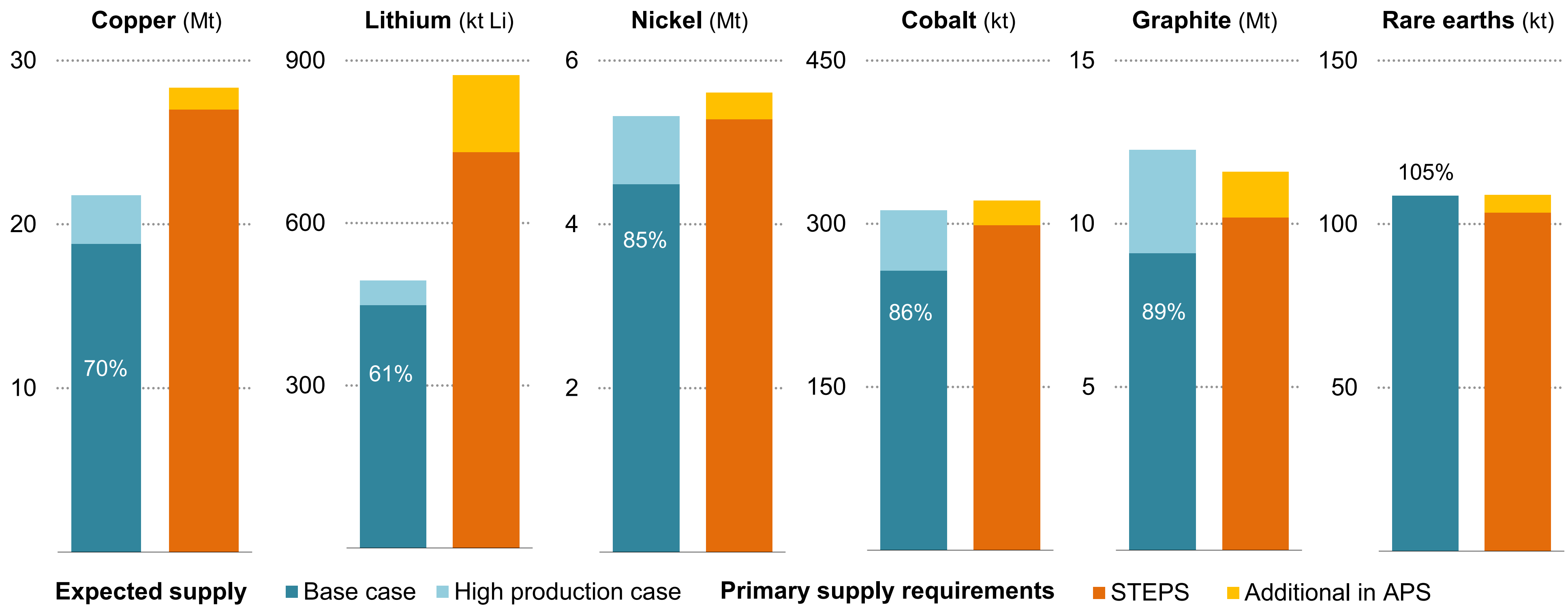
Market value of mined and refined materials by region in the base case



Notes: MER = market exchange rates. The **base case** includes production from existing assets and those under construction, along with projects that have a high chance of moving ahead. Market value was calculated by multiplying each region's production volume in the base case with today's market price for final products, taking into account refining margins. Assessed based on the six focus minerals – copper, lithium, nickel, cobalt, graphite and rare earth elements.

Expected supply from announced projects suggests improving supply-demand balances, with major exceptions for copper and lithium

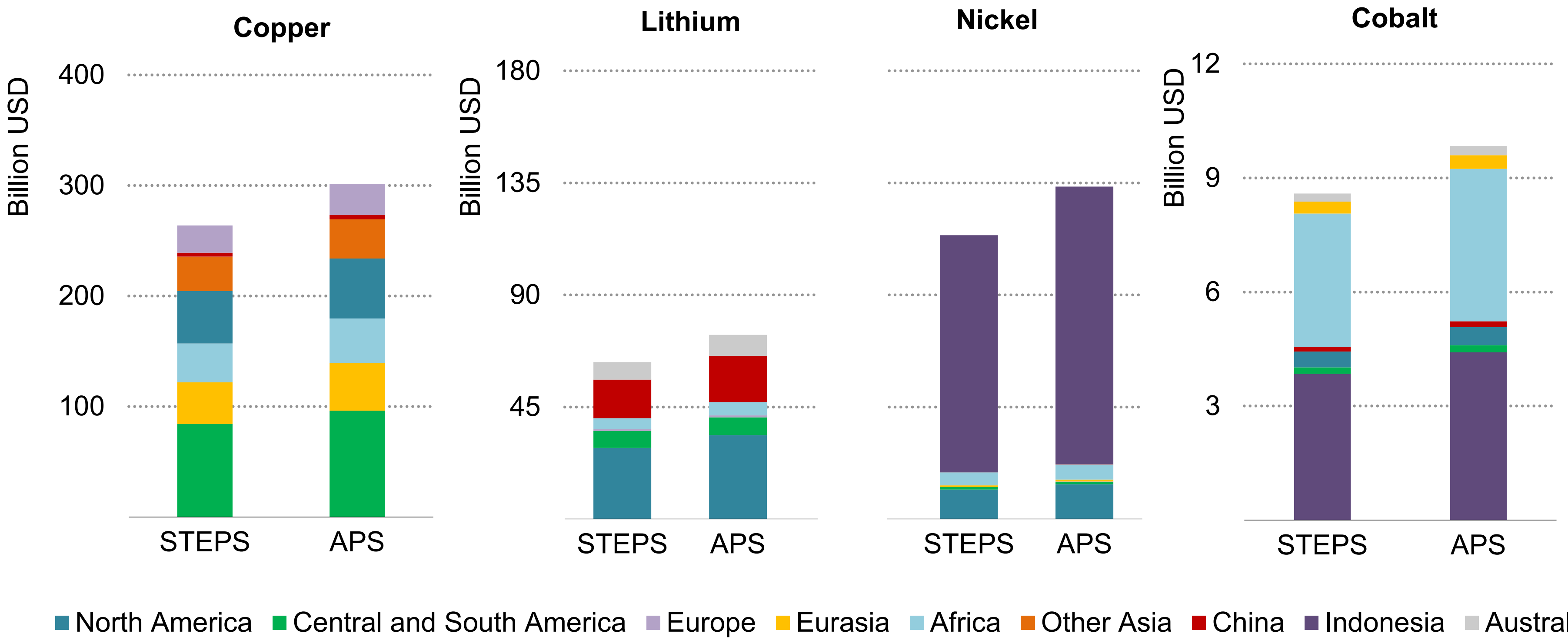
Expected mine supply from existing and announced projects and primary supply requirements for key energy minerals, 2035



Notes: The percentage values indicate the share of base case supply against 2035 primary supply requirements in the STEPS. Expected supply is based on mined or raw material output based on announced projects, except for graphite where the figure refers to the sum of natural flake 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.

Around USD 500 billion in new capital investment is required for mining between now and 2040 under the STEPS, rising to around USD 600 billion in the APS

Mining capital requirements by mineral and region to meet demand in the STEPS and APS



Notes: Regional investment is calculated by assuming that investment to meet demand occurs by the same regional breakdown as projected production growth in base case. Capital requirements for the STEPS and APS 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.

Demand for critical minerals is set to grow rapidly driven by energy technologies; announced projects are catching up with demand growth though supply gaps exist for copper and lithium

Demand outlook

Demand for key energy minerals is set to grow rapidly across all scenarios, with the largest source of growth coming from the clean energy sector. In the Stated Policies Scenario (STEPS), lithium grows fivefold from today to 2040, while graphite and nickel demand double. Demand for cobalt and rare earth elements also grows strongly, increasing 50-60% by 2040. Copper is the material with the largest established market, and its demand is projected to grow by 30% over the same period. Battery deployment in electric vehicles (EVs) and storage applications drives strong demand growth for lithium, graphite, nickel and cobalt demand. Meanwhile, expanding construction and the electrification of grids and industrial equipment are fuelling increased copper demand. Growing demand for permanent magnets, particularly from EVs and wind power, boosts the need for magnet rare earths.

While projections for renewable energy, grid expansion and storage deployment remain strong, a downward adjustment in projected EV sales growth in this year's Outlook has brought down mineral demand for some battery metals. Cobalt demand has been affected by the growing adoption of lithium iron phosphate (LFP) chemistries, with projected 2040 demand now over 10% lower than last year's Outlook.

Supply outlook

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. Neither case considers projects that are in very early stages of development or includes speculative projects.

In recent years, there has been a growing number of announcements for new mining and refining projects targeting key energy minerals, pointing to a notable increase in future production volumes. In most cases, projected supply volumes for 2040 have been revised upwards in this year's Outlook to reflect these developments. The combined market value for mining of the six focus energy minerals – copper, lithium, nickel, cobalt, graphite and rare earth elements – increases by 50% in the base case, reaching USD 500 billion by 2040. While copper maintains the largest share of the combined market value, lithium sees the fastest growth, increasing fivefold to

2040. Central and South America captures the largest market value for mining, driven by substantial copper production in the area. The People's Republic of China (hereafter, "China") claims nearly 50% of the projected market value for refining. Australia and Africa also experience a substantial increase in their mining market value, while Europe registers some gains in refining.

Based on the mining project pipeline in the base case, overall supplies of some key energy minerals are on track to meet projected demand under today's policy settings in the STEPS. Copper and lithium are major exceptions where expected mined supply from announced projects falls short of projected demand in 2035, with implied deficits of 30% for copper and 40% for lithium in the STEPS. Even in the high production case, both copper and lithium see notable supply shortfalls. The supply gap for copper is particularly concerning due to declining ore grades, rising project costs and a sharp slowdown in new resource discoveries, all of which make bringing new supply online highly challenging. For lithium, while the market is poised to be well-supplied in the near term, rapidly growing demand is projected to turn market balances into deficits by the 2030s although the prospects for developing new lithium projects are stronger than for copper.

Long-term supply gaps for nickel and cobalt are narrowing, especially as there is a host of projects being planned at a relatively early stage. If these projects come online as scheduled, as in the high production case, expected nickel and cobalt supply could cover demand in the STEPS in 2035. Rare earth elements appear to be sufficiently supplied in 2035 based on the project pipeline. However, supply concentration for rare earths and graphite remains a key vulnerability.

Market balance results are not set in stone, and there are considerable uncertainties over how they will evolve in practice. Where gaps are identified between future demand and supply based on announced projects, it is important to note that these are *implied* gaps. In reality, if supply proves inadequate, this will push up prices in ways that curtail demand, resulting in slower or more expensive deployment of clean energy technologies. At the same time, these gaps could potentially be closed through the development of additional projects and scaling up recycling efforts. The results should not be interpreted to mean that energy transition goals are unattainable due to material constraints. Similarly, when supply appears sufficient, these outcomes are not guaranteed, as projects could still face delays and cost overruns, requiring strengthened efforts to bring projects online on time and within budget.

The shifting battery technology landscape, particularly the rapid rise of LFP chemistries, has brought increased focus on two additional materials that have received relatively less attention: battery-grade manganese sulphate and high-purity phosphoric acid. While mining is less of a bottleneck for these materials, the rapid surge in demand underscores the need for expanded refining capacity, particularly in geographically diverse regions, to prevent potential supply constraints (see Chapter 3 on emerging battery supply chains).

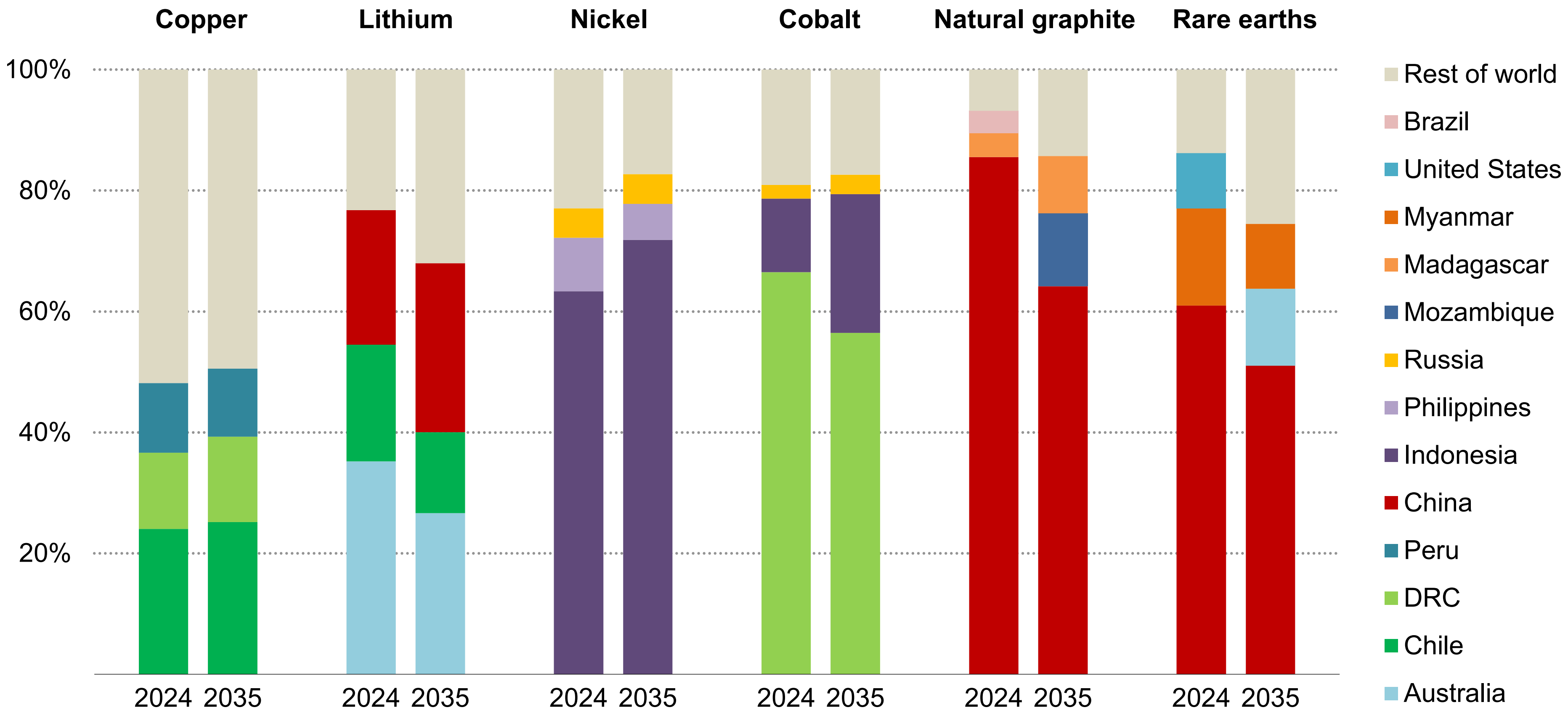
Investment outlook

Meeting the rising demand for critical minerals under both the STEPS and APS would require substantial investment for new mines and refineries. In the STEPS, around USD 500 billion in new capital investment is required for mining between now and 2040. In the APS, as mineral demand rises more rapidly, capital requirements are about 15% higher at USD 600 billion over the same period (excluding sustained capital expenditure). These amounts reflect not only the scale of demand growth, but also the increasing capital intensity for new projects, driven by declining ore quality, particularly in more mature markets such as copper.

Among the minerals, copper sees the largest capital requirements at about USD 350 billion in both the STEPS and APS. Nickel similarly faces high levels of required investment. These needs span across regions, involving both brownfield and greenfield projects. If these production additions occur following the same regional breakdown as from 2024 to 2040 in our base case, we estimate that Central and South America, Indonesia and North America to see the highest levels of investment, each amounting to around USD 100 billion of investment in both the STEPS and APS. Investment in these regions is driven by copper, nickel and lithium. Africa also sees approximately USD 50 billion in investment, largely driven by copper mining. For cobalt, investment will largely occur in Africa and Indonesia, each seeing approximately USD 4 billion of investment.

Mining of critical minerals is set to become more concentrated for copper, nickel and cobalt while more diversified for lithium, graphite and rare earth elements

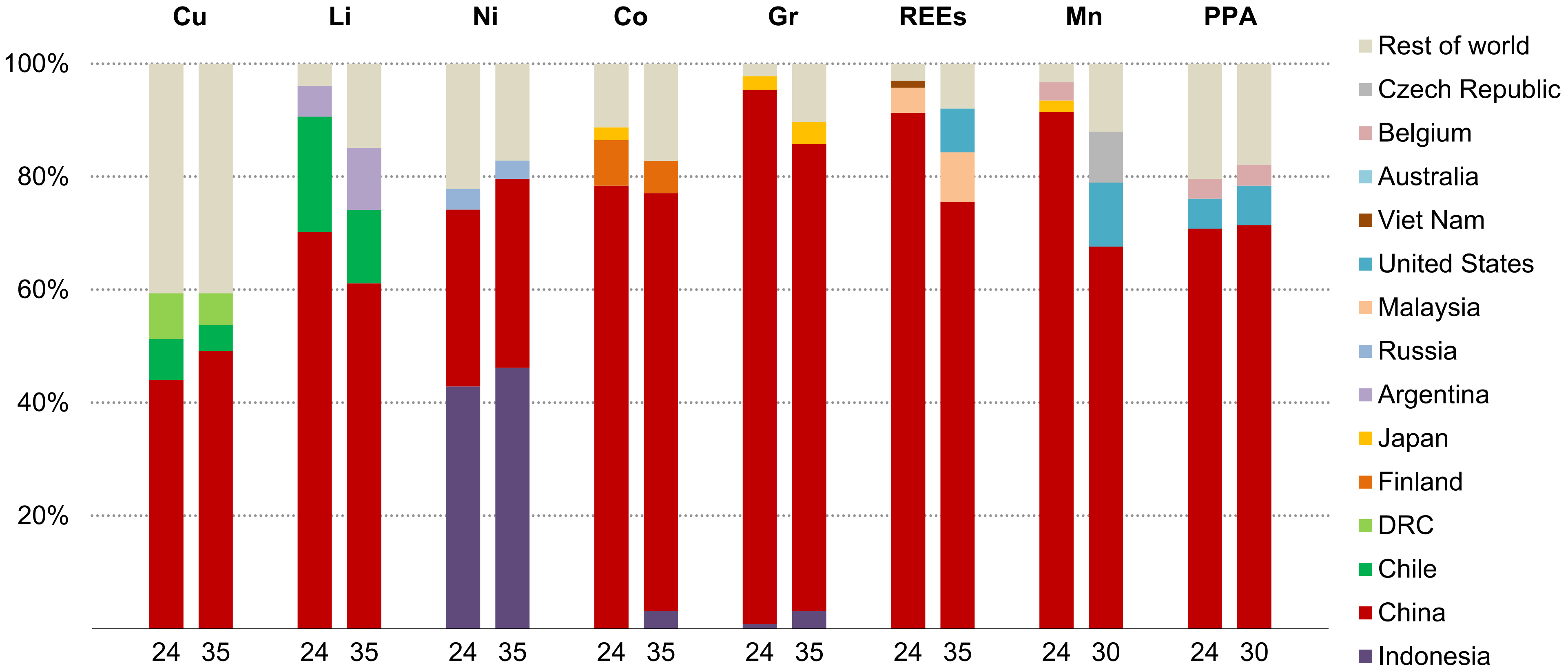
Geographical distribution of mined or raw material production for key energy minerals in the base case



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.

Refined material production is also set to remain highly concentrated in a few countries

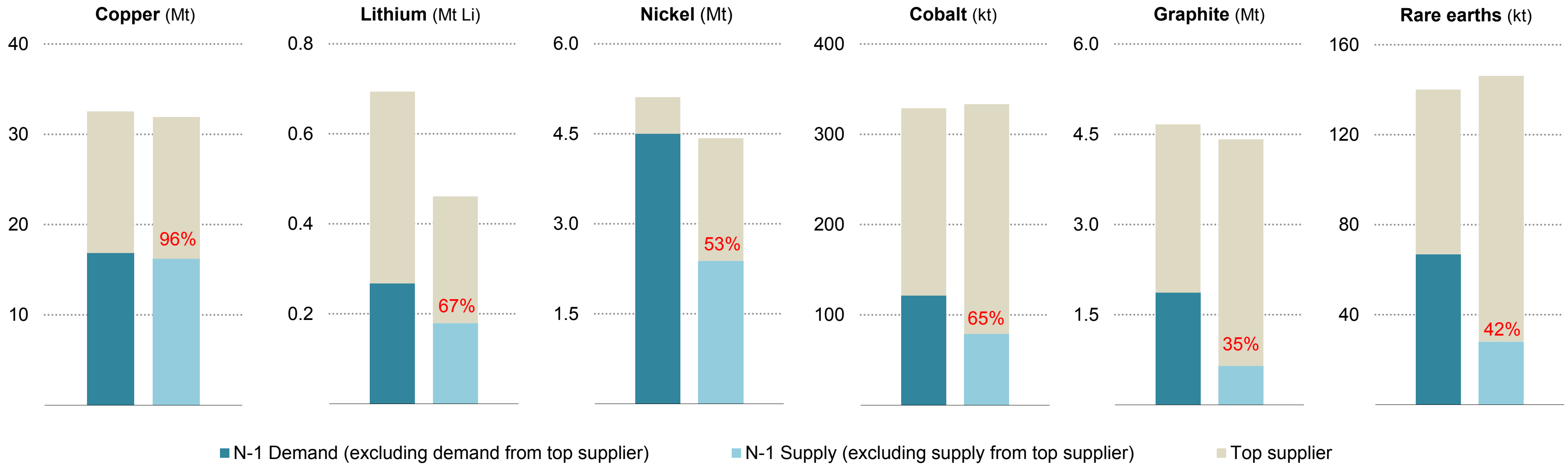
Geographical distribution of refined material production for key minerals in the base case



Notes: Cu = copper; Li = lithium; Ni = nickel; Co = cobalt; Gr = graphite; REEs = rare earth elements; Mn = battery-grade manganese sulphate; PPA = battery-grade purified phosphoric acid; DRC = Democratic Republic of the Congo. The figures for graphite are based on battery-grade including spherical graphite and synthetic graphite. The figures for rare earths are for magnet rare earth elements only. The figure depicts the value of the top three producing countries in a given year.

Reliance on a small number of suppliers increases vulnerability to shocks and disruptions, even in a well-supplied market

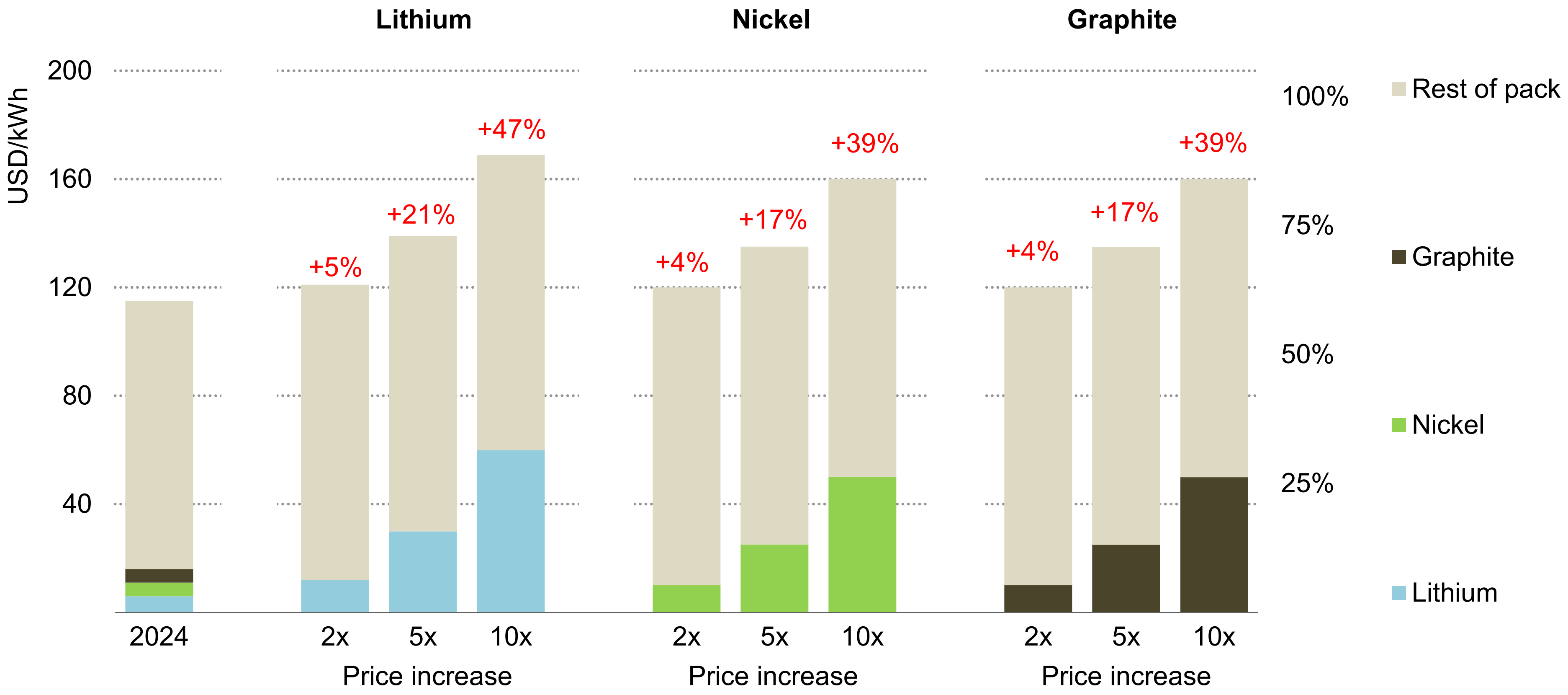
N-1 material requirements and N-1 refined material supply in the STEPS, 2035



Notes: The N-1 supply excludes the production volumes from the largest producer from the total global supply, and N-1 demand excludes 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 earths are for magnet rare earth elements only.

A battery mineral price shock could increase global average battery pack prices by 40-50% resulting in higher prices for consumers…

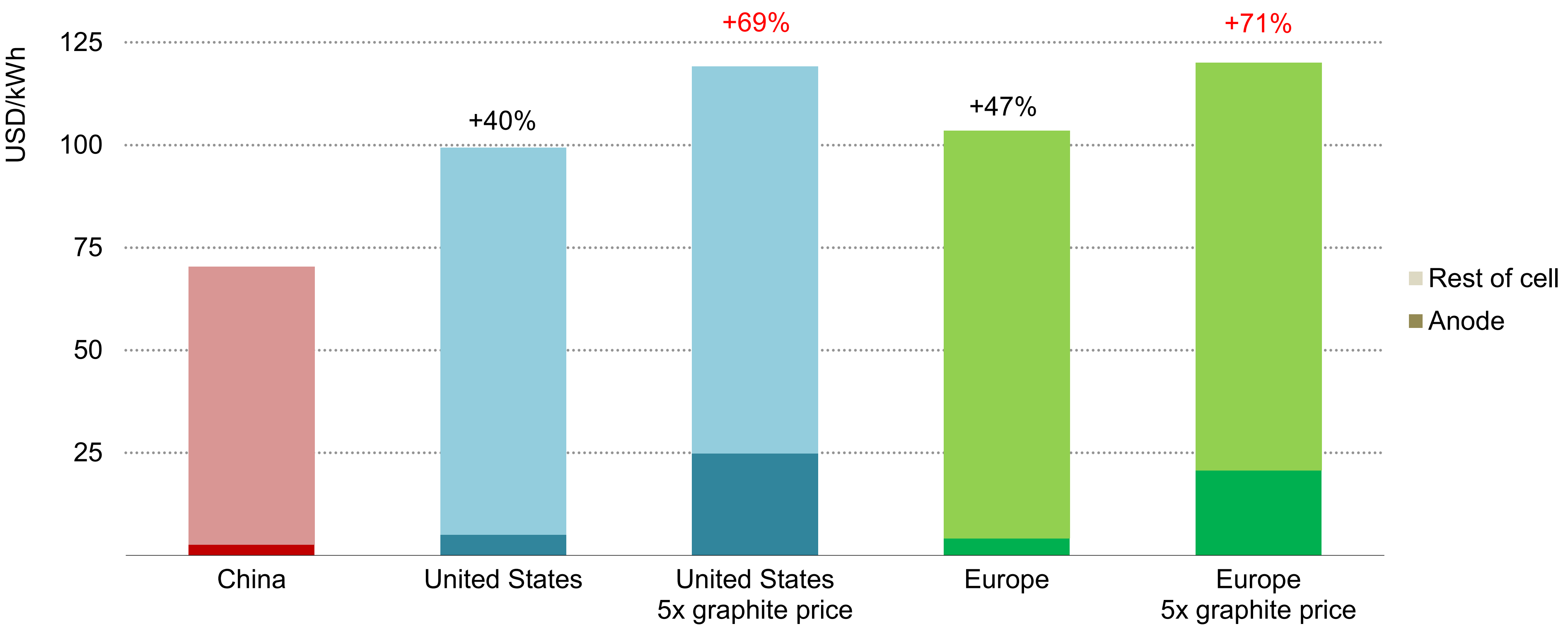
Battery pack price increases at different battery metal price levels



Notes: kWh = kilowatt-hour. Based on 2024 global average battery pack prices including all chemistries and 2024 material prices.
Sources: IEA analysis based on BloombergNEF and S&P Global.

… and dramatically reducing manufacturing competitiveness, widening the battery manufacturing cost gap with China from 40-50% to 70% for Europe and the United States

Battery cell levelised cost of production by region at different graphite price levels



Note: Based on levelised cost of production for battery cells in 2023. Representative of 2023 global average lithium-ion battery chemistry mix.
Source: IEA analysis based on the [IEA ETP Manufacturing and Trade model](#).

High supply concentration across critical minerals markets increases vulnerability to supply shocks and disruptions

Concentration

Based on the project pipeline, the geographical concentration of mining operations is set to remain high for most minerals. Mined supply is set to increase in concentration in the top three countries for copper, nickel and cobalt by 2035. In 2035, the top three producing countries for nickel supply 85% of the market, up from 75% in 2024. Indonesia is set to see significant supply growth in both nickel and cobalt markets over the next decade. There is some diversification emerging in the mining of lithium, graphite and rare earth elements. The share of mined lithium supply from the top three producers is set to fall below 70% by 2035, down from over 75% in 2024. Graphite and rare earth elements also see some improvement as new mining suppliers emerge over the next decade – Madagascar and Mozambique for graphite and Australia for rare earths.

However, refining operations for most minerals are set to remain highly concentrated over the next decade. Refining concentration increases significantly for nickel due to major growth in supply in Indonesia. Despite some diversification occurring for lithium, graphite, rare earths and battery-grade manganese sulphate, China remains the dominant refined supplier for almost all minerals. In 2035, China is set to supply over 60% of refined lithium and cobalt, and around 80% of battery-grade graphite and rare earth elements. By 2030, China is set to supply 70% of battery-grade manganese sulphate and 75% of purified phosphoric acid.

Security implications

This high market concentration means there is a risk of significant shortfalls in supply if, for any reason, supply from the largest producing country is disrupted. In natural gas markets and whole energy systems, resilience analysis, often called “N-1” assessment, is used as a tool to understand potential vulnerabilities in the system. Conducting this N-1 assessment in the critical mineral context can provide useful insights into how the system may look when the largest supplier is excluded from global supply and demand balances. The supply remaining after excluding the largest supplier is known as the N-1 supply. We compared this with N-1 demand, which excludes the consumption of the largest supplier.

Nickel, cobalt, graphite and rare earth elements appear relatively well-supplied on a global basis in 2035 in the STEPS. However, if the largest supplier and its demand is excluded (China for lithium, cobalt, graphite and rare earths, and Indonesia for nickel), the picture becomes starkly different. The remaining N-1 supplies would fall significantly below N-1 demand. For graphite and rare earth elements, the remaining supplies would cover only 35-40% of N-1 demand in 2035, entirely insufficient to meet the mineral needs. The N-1 supply covers less than 55% of N-1 demand for nickel, but the ratio would be much lower if battery-grade nickel sulphate supplies (mostly from China) were also disrupted. For lithium and cobalt, the gap is less stark, but the remaining N-1 supply still covers only 65% of N-1 demand for both. This emphasises that even where the overall global balance is reasonably well-supplied, critical mineral supply chains can be highly vulnerable to supply shocks, whether from extreme weather, trade disruptions or geopolitics. Copper is the only critical mineral where the N-1 supply almost covers N-1 demand, as China is the largest consumer of refined copper as well as its leading supplier.

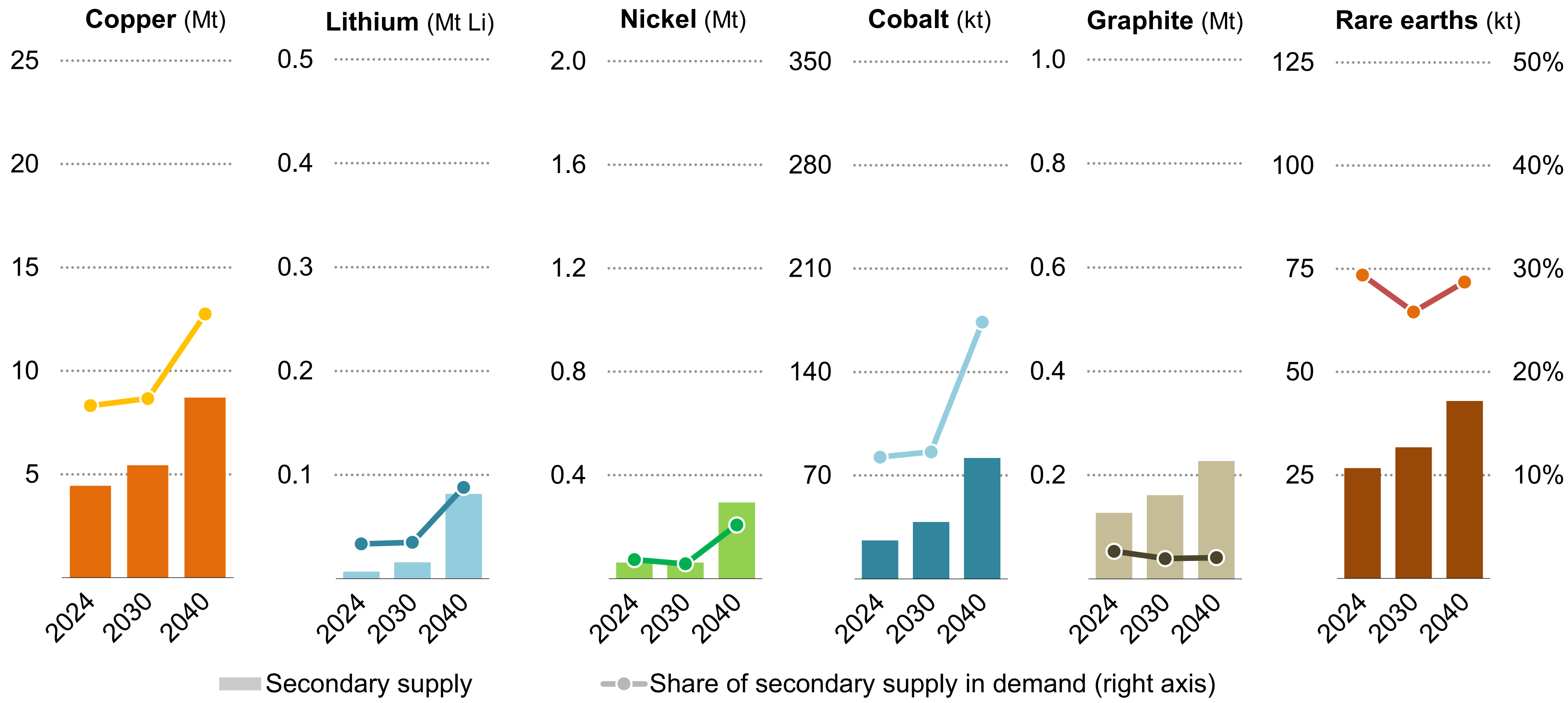
Disruptions in mineral supplies can have major impacts on technology prices, manufacturing competitiveness, inflation and the wider economy. Spikes in battery metal prices caused by disruptions can drive up the cost of both batteries and EVs, potentially hindering the pace of electrification and causing significant economic consequences. In 2010, the price of rare earth elements spiked by as much as ten times when China held back exports. If a lithium, nickel or graphite supply disruption were to occur, causing a fivefold price surge, average battery pack prices globally would increase by 20%. In the case of tenfold price increases, battery prices would go up by 40-50%, substantially reducing their competitiveness. This could result in more expensive EVs, reducing affordability for consumers and slowing adoption.

Mineral supply shocks and disruptions can also strongly hinder plans to develop diversified energy technology manufacturing supply chains. Today, the battery manufacturing cost-competitiveness gap among economies is already stark with the levelised cost of production of battery cells 40-50% higher in Europe and the United States (US) than in China. Higher mineral prices, resulting from restricted Chinese supply to international markets, could widen this manufacturing cost gap further between today's top producer and other regions. A supply shock resulting in graphite prices increasing fivefold would further widen this cost gap to 70% for both economies, making their manufacturing significantly less competitive, with strong potential implications for industrial developments and jobs. Prolonged disruptions could also lead to major revenue and job losses for manufacturers, with significant economic consequences for economies with growing battery manufacturing bases, such as Europe, Japan, Korea and the United States.

The International Energy Agency (IEA) Critical Minerals Security Programme was established in 2022 to support governments in strengthening critical mineral security. As highlighted in the Future of Energy Security Summit in April 2025, the IEA will continue to expand activities to strengthen critical minerals security including in areas such as resilience against potential disruptions, tools to accelerate project developments in geographically diverse regions, and deepening work on market monitoring and early warning mechanisms.

Secondary supply increases rapidly post-2030 as a growing amount of end-of-life feedstock becomes available

Secondary supply volumes and share of total demand for key energy minerals in the STEPS



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

Scaling up recycling can bring greater security and sustainability benefits; strategic efforts are needed to improve recycling rates

Recycling can bring multiple benefits in ensuring reliable and sustainable critical mineral supplies. While recycling does not eliminate the need for sustained mining investment, it creates a valuable secondary supply source that reduces reliance on new mines and enhances supply security for countries importing minerals. Expanding recycling infrastructure can also help build reserves to buffer against future supply disruptions. Moreover, scaling up recycling mitigates the environmental and social impacts related to mining and refining while preventing waste from end-use technologies ending up in landfills.

A successful scale-up of recycling can lower the need for new mining activity by 5-30% by 2040 in the STEPS. With increasing feedstock availability thereafter, recycling reduces the need for new mine development by 35% for copper and cobalt over 20% for lithium and 15% for nickel by 2050. In a scenario which meets climate pledges, this increases to 25-40%. Enhancing critical minerals recycling offers substantial financial and sustainability benefits, reducing mining investment needs by around 30% through 2040. Recycling can also mitigate the environmental and social impacts associated with mineral production. On average, recycled energy transition minerals such as nickel, cobalt and lithium incur 80% less greenhouse gas emissions than primary materials produced from mining.

In order to ensure secure and sustainable mineral supply chains, a redoubling of efforts to scale up all forms of recycling, urban mining and mine waste treatment is needed. Long-term policy visibility is central to providing the confidence investors and recyclers need to commit to new projects. Clear targets and intermediate milestones need to be set to provide investors with clarity on policy direction.

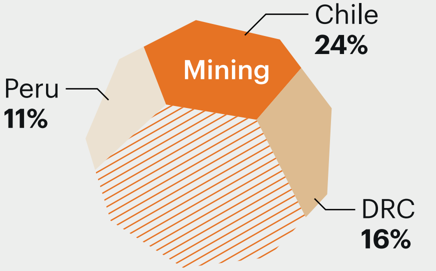
Support for domestic recycling infrastructure, especially material recovery, is crucial as otherwise processed feedstock such as black mass needs to be exported for further processing elsewhere. For batteries, the concurrent development of midstream value chains that consume recycled material should also be taken into account as part of the broader strategy. Efforts also need to include tighter recycling regulation and mandates, such as extended producer responsibility, along with greater enforcement to prevent waste from ending up in landfills; steps to minimise unmanaged leakage of recyclable battery waste; improvements to collection rates by comprehensive collection and take-back systems, notably for copper, permanent magnets and batteries, are all crucial; and research, development and demonstration support for novel emerging recycling technologies such as advanced scrap sorting and new chemical and physical processes that allow the recycling of low-grade feedstock.

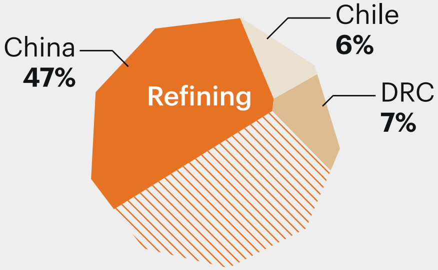
Outlook for copper

Copper

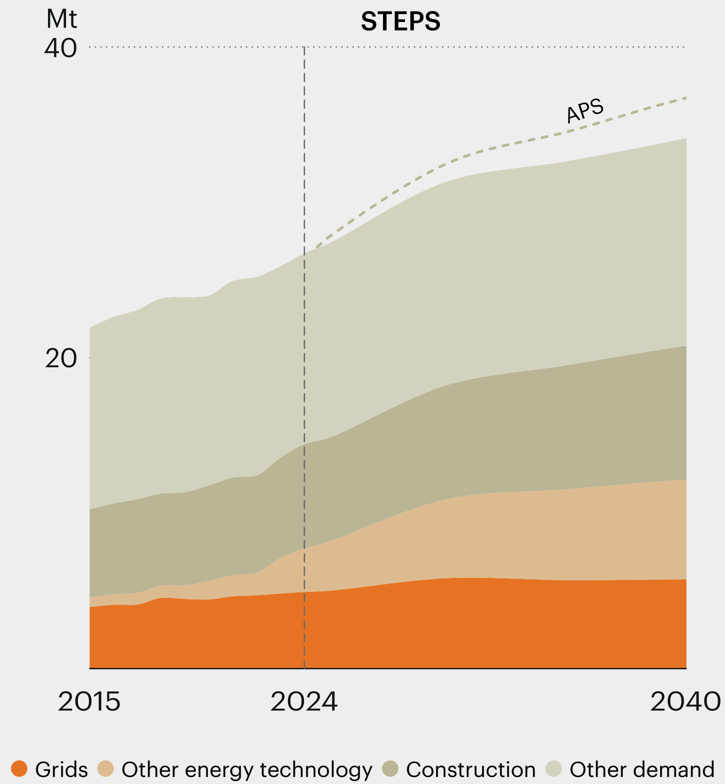
Cu

Top three producers 2030

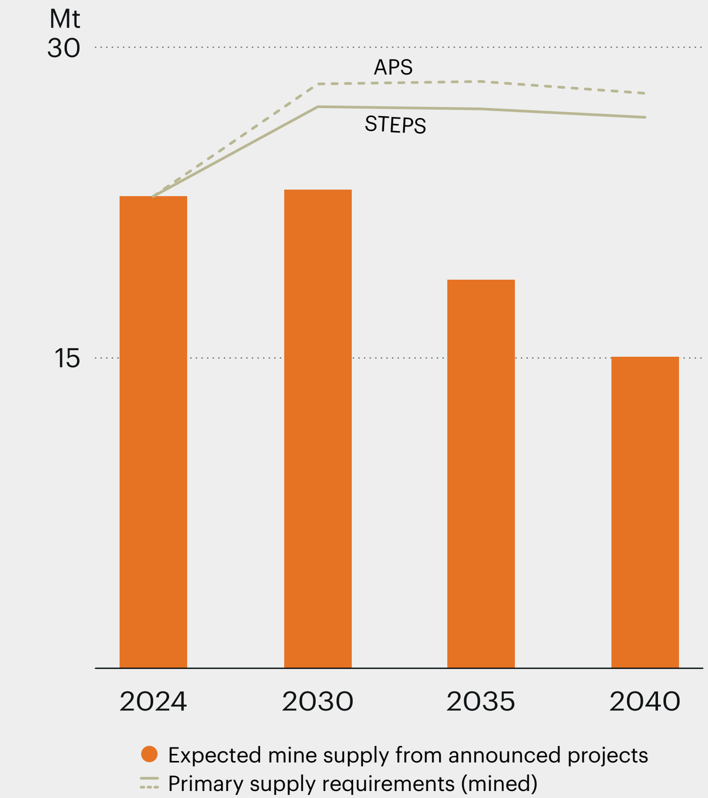




Demand outlook



Mining requirements



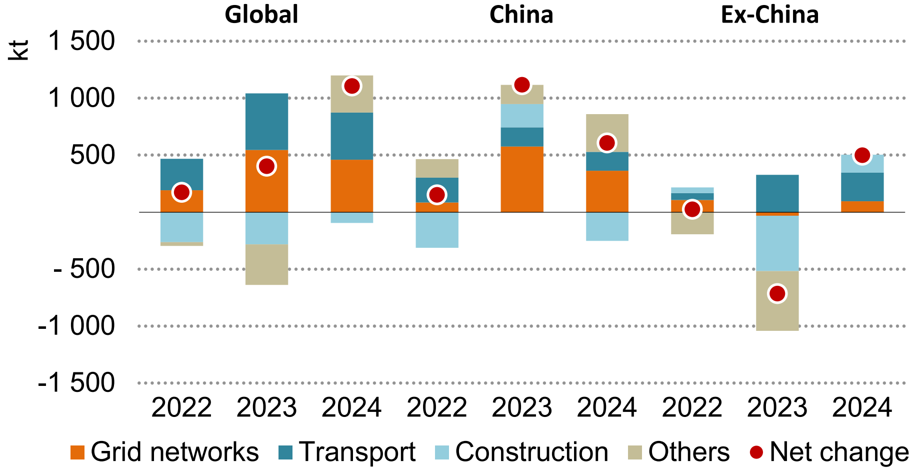
STEPS	2021	2024	2030	2040
Cleantech demand (kt)	**6 002**	**7 737**	**10 910**	**12 162**
Other uses (kt)	18 944	18 980	20 438	21 975
Total demand (kt)	**24 946**	**26 717**	**31 348**	**34 137**
Secondary supply and reuse (kt)	4 123	4 441	5 431	8 702
Primary supply requirements (kt)	**20 851**	**22 503**	**25 917**	**25 428**
Share of top three mining countries	46%	48%	50%	53%
Share of top three refining countries	57%	59%	60%	60%

Recent market developments: Surge in Chinese smelter capacity drives fees negative raising concerns for increasing market concentration

Demand for refined copper increased 3.2% in 2024, up from 2.7% in 2023 and 1.1% in 2022. Contrasting with 2023 where global growth was almost entirely driven by China and India, in 2024 ex-China regions experienced robust growth, particularly in India, Saudi Arabia and Malaysia, driven by rapid infrastructure development and building construction. China experienced weaker growth than in 2023 primarily due to the property sector downturn. Elevated inflation, interest rates and energy costs continue to hinder growth in Europe, which saw its second year of demand contraction.

Copper prices experienced significant volatility in 2024, reaching as high as USD 10 800/tonne before falling away the rest of the year. Price increases were initially driven by tightening concentrate market balances from key mine disruptions including the shutdown of Cobre Panama and the downgraded production guidance by Anglo American. However, the concentrate deficit was predominantly driven by a surge in new smelter capacity in China, pushing spot treatment and refining charges (TC/RCs) to record lows as smelters competed to secure copper concentrate. In contrast, refined copper experienced a surplus due to weaker demand from China's property sector, leading to inventory build-up and downward pressure on prices. However, prices were buoyed towards the end of the year by several factors including the US Federal Reserve's decision to start cutting interest rates, the announcement of Chinese economic stimulus measures.

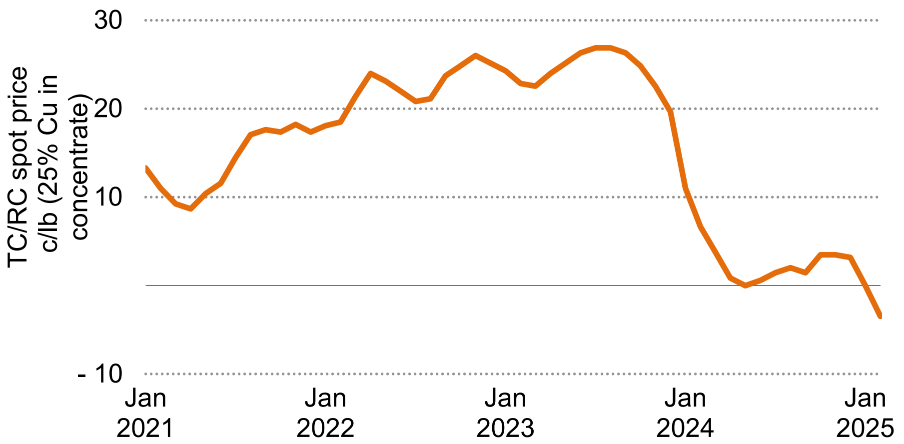
Change in annual copper consumption by sector and region



Note: Includes direct-use scrap.

In early 2025, copper prices were continuing to rise due to two primary factors. First, after the 25% tariff on aluminium and steel implemented by the United States, and an announced probe into US copper imports, markets were already pricing in higher costs for imports to the United States. Second, a weakening dollar was making copper more affordable for many buyers. However, after the major tariffs announced by the United States in April 2025, copper prices dropped due to concerns about a global economic slowdown and ongoing uncertainty, and remained lower even after the announcement of a 90-day pause on many of the measures. China's retaliatory tariffs could also affect the market. The United States is China's largest source of copper scrap, and the blanket tariff from China appears to include copper scrap imports. Overall, the uncertain economic environment is raising concerns about reduced copper demand and weaker supply investment in 2025.

Copper smelter spot treatment and refining charges, 2021-2025

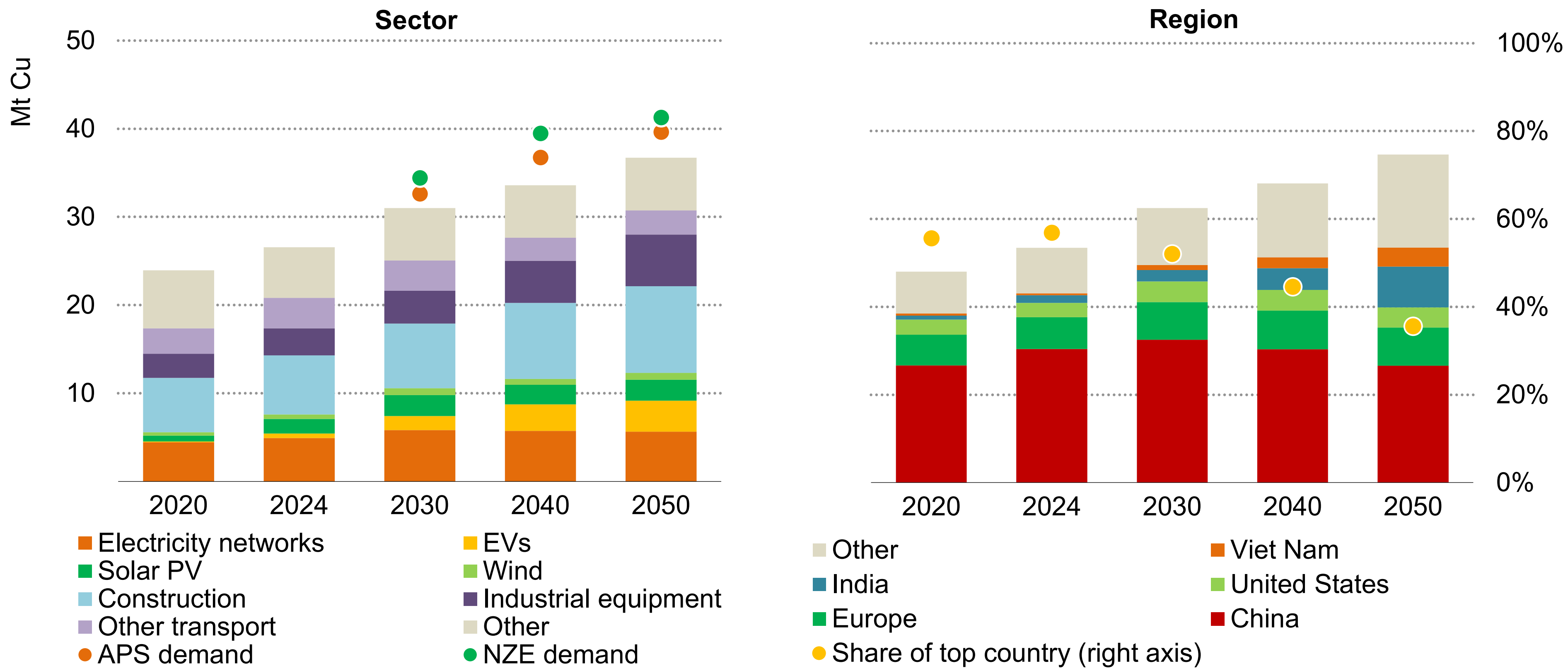


Notes: TC/RC = treatment and refining charges; c/lb = cents per pound. Chinese smelter purchase price (cost, insurance and freight basis).
Source: IEA analysis based on Wood Mackenzie.

However, the copper smelting industry still faces major challenges, with smelters around the world struggling to compete with Chinese smelters, as spot TC/RCs hit record lows, being negative since December 2024 due to the excess smelter capacity. Glencore recently announced it was halting operations in its Pasar smelter in the Philippines due to the challenging market conditions. Despite the negative spot TC/RCs squeezing margins, many smelters make most of their revenue from long-term contracts around a benchmark price which is also falling significantly, expected to be little over USD 20 per tonne in 2025 down from USD 80 per tonne last year. There is growing concern about more ex-China closures, with risks of a situation similar to the nickel market in recent years, where ex-Indonesia projects shut down due to low prices resulting from excess supply.

Demand: Construction, grids, industrials and EVs drive growth in copper demand with China the leading demand driver, though new major demand centres emerge in India and Viet Nam

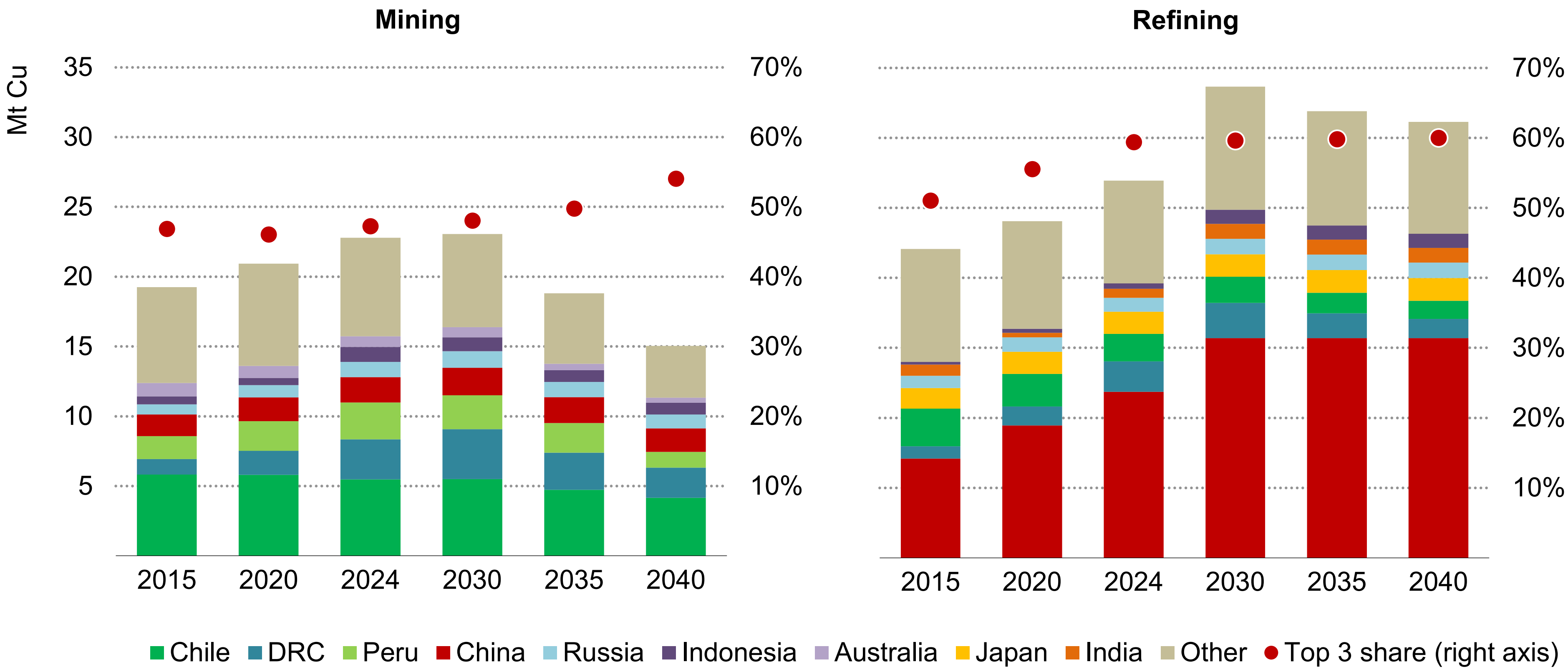
Copper demand by sector and region in the STEPS



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

Supply: The DRC cements itself as the second-largest copper mining producer after Chile, while China maintains its dominance in copper refining

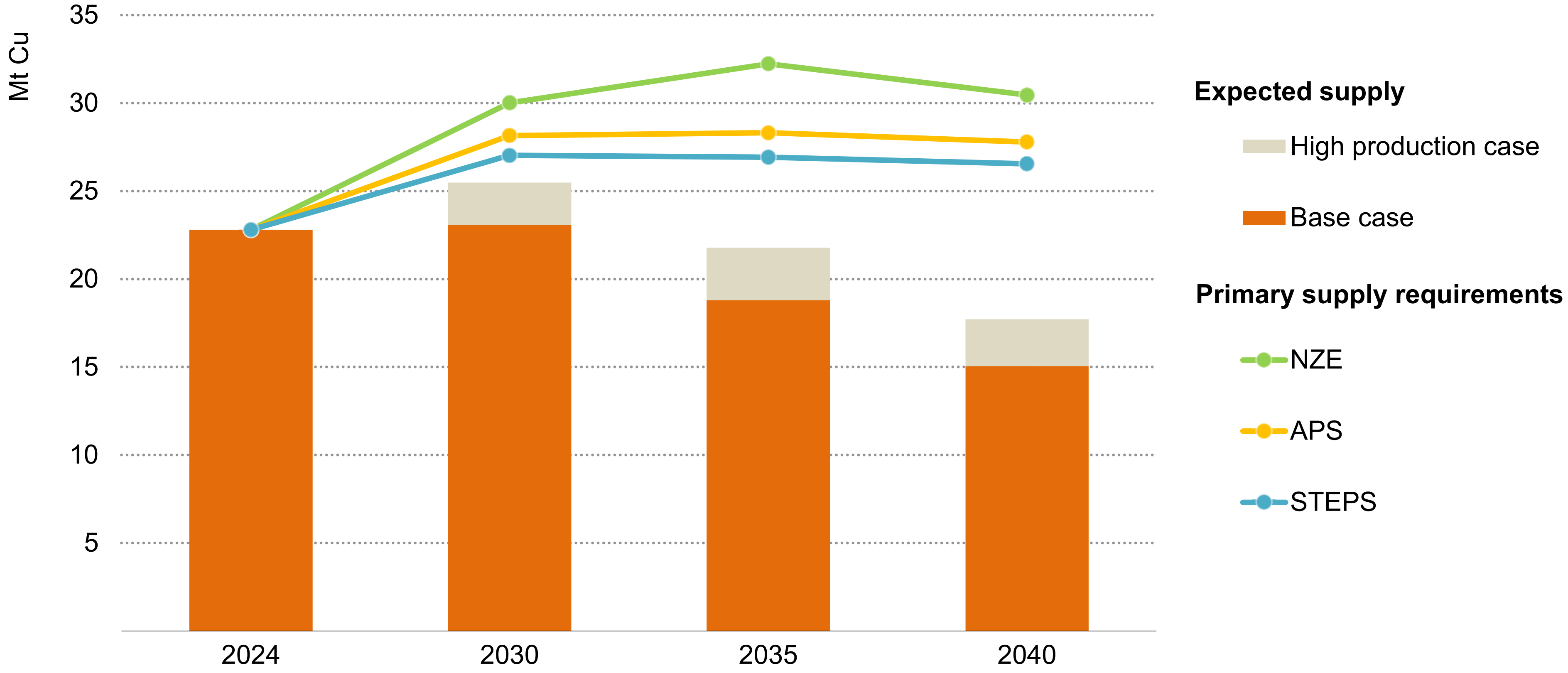
Copper production from operating and announced projects in the base case



Notes: DRC = Democratic Republic of the Congo. Refined supplies are independently assessed based on announced refining projects and are not constrained by mined supply. Refining also includes both primary and secondary refining.

Supply: A major primary copper supply deficit develops later this decade

Mined copper 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 Overview section for definitions of the base and high production cases.

Implications: Declining ore grades, rising costs and fewer resource discoveries are driving the copper supply deficit; both new investment and demand-side measures are needed

Demand outlook

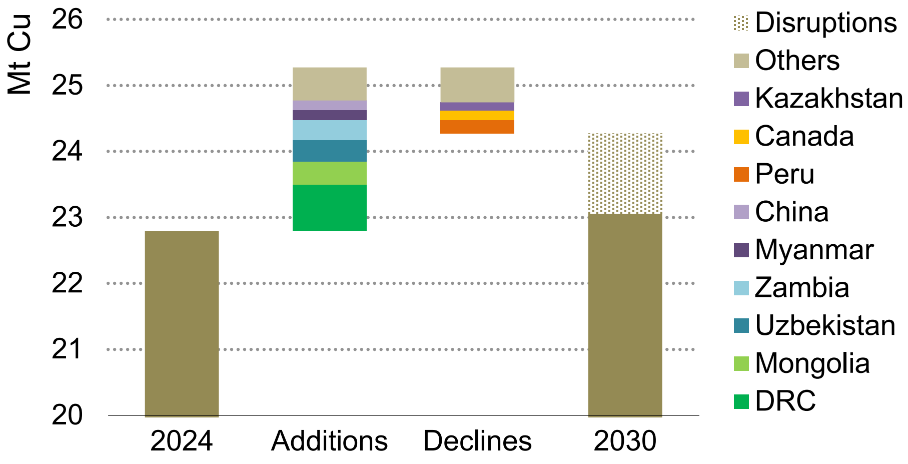
Global refined copper demand (excluding direct-use scrap) was almost 27 million tonnes (Mt) in 2024 and grows to reach almost 33 Mt in 2035 and 37 Mt in 2050 in the STEPS. Construction and electricity networks remain the largest sources of copper demand, while EVs are the fastest-growing source of demand, increasing sevenfold from 2% of global copper demand in 2024 to 10% in 2050 in the STEPS. Demand from industrial machinery and equipment almost doubles in the same time to reach over 15% of demand, driven by the increase in manufacturing and electrification across the world, while demand from solar, wind and construction all increase around 50% in this period. China alone was responsible for almost 60% of global refined copper demand in 2024. The United States was the second-largest source of demand with just over 6% of demand, with Germany the third-largest source with 4% in 2024. Together Europe was responsible for 14% of global refined copper demand in 2024.

Looking ahead, major new sources of refined copper demand emerge in Asia outside of China. India rapidly overtakes the United States to become the third-largest source of refined copper demand, with over 10% of global demand in 2050 in the STEPS, up from just 3% in 2024. Viet Nam also emerges as a major consumer with 6% of global demand in 2050, up from just 1% of demand in 2024. Industrialisation, infrastructure development, population expansion, urbanisation and industrial migration out of China are the driving forces for the growth in refined consumption in these regions. Lower production costs and growing end-use demand make India and Viet Nam attractive for investment in copper semis manufacturing, driving increased refined copper consumption. During this time, China's share of global refined copper demand almost halves to be around 35% in 2050, due to its increasing economic maturity driving a slower expansion of construction and manufacturing sectors and thus refined copper demand.

Supply outlook

Global mined copper supply reached 22.8 Mt in 2024. Chile remains the largest producer, supplying a quarter of global output. The DRC extended its lead in mined production over Peru in 2024 to remain the second-largest producer. Based on the current project pipeline in the base case, global mined supply peaks around the late 2020s at a little over 24 Mt, after which output declines noticeably to less than 19 Mt by 2035 due to a combination of declining ore grades, asset retirements and reserve depletion. The major near-term growth is set to come from the DRC from major projects such as Kamoa-Kakula and Tenke Fungurume, which are slated to ramp up output to over 1.3 Mt by 2028 from 900 kilotonnes (kt) in 2024. The Oyu Tolgoi expansion in Mongolia is another key project driving supply growth later this decade, with production set to reach around 600 kt by 2028. There is also some near-term growth from large projects in Latin America including Collahuasi (Chile), Quebrada Blanca (Chile) and Las Bambas (Peru); however, production in the region peaks earlier, declining after the late 2020s.

Copper mining additions and declines in the base case

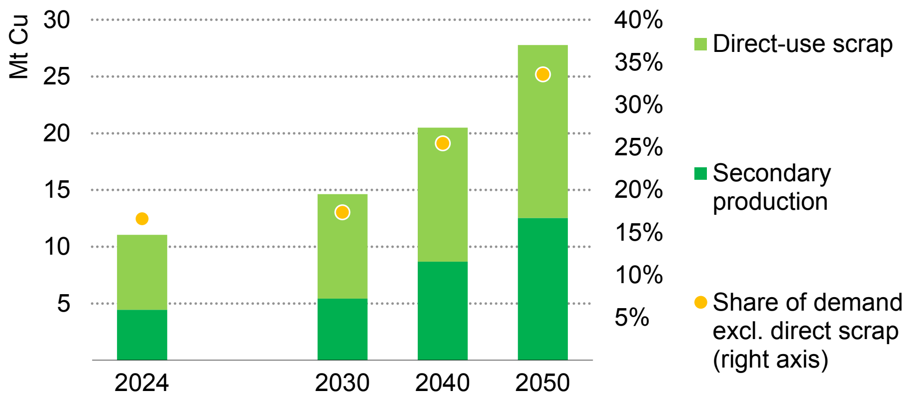


Note: DRC = Democratic Republic of the Congo.

Despite African copper mining projects standing out with higher-grade deposits, rapid recent growth and competitive capital intensities, their deposits are typically sediment-hosted, in contrast to the porphyry deposits in Latin America, meaning the African deposits are more concentrated with sharp boundaries, driving a more rapid depletion of these reserves in the future.

China maintains dominance of global refined copper supply with 45% of production in 2024, with strong growth to continue based on the current project pipeline, with several new plants and expansions. In 2024, the DRC overtook Chile to be the world's second-largest copper refiner, producing 8% of global supply. Based on the pipeline there is little diversification set to occur on the refining side. China is set to grow its share of total production to 50% by 2040. Refining capability based on the global pipeline including secondary production is set to be over 33.5 Mt by 2030.

Secondary supply copper outlook in the STEPS



Note: Secondary supply copper volumes are recovered from recycling from secondary production and direct-use scrap, accounting for collection and recycling process yield losses.

The share of secondary copper supply in total demand (excluding direct-use scrap) is less than 17% in 2024 declining from 18% in 2015. This is due to the combination of rapidly growing demand, lower prices, scrap trade restrictions from China, higher energy and shipping costs reducing recycling profitability, and the fact that EU and US policies promoting domestic scrap collection have yet to take effect. With policy action to increase collection rates of copper supply from secondary sources, the share of secondary copper supply in total demand (excluding direct-use scrap) grows to almost 35% in the STEPS by 2050.

Supply and demand balances

Based on the pipeline of existing and announced copper mining projects, there is set to be a 30% supply deficit by 2035 in the STEPS. This supply gap widens to 35% in the APS and over 40% in the NZE Scenario in the same year. Even in the high production case, there is a 20% supply deficit by 2035 in the STEPS. The supply deficit starts forming from around the late 2020s in the base case and slightly later in the high production case under the STEPS. This supply gap is driven by declining copper ore grades – the average grade of copper mines has decreased 40% since 1991. This is only partly explained by processing advances such as solvent extraction and electrowinning unlocking lower-grade deposits, and is predominantly due to reserve exhaustion. These declining grades have increased capital costs and complexity for expansions and new projects, deterring investment. In the leading supply region, Latin America, average brownfield project capital intensities have increased 65% since 2020, approaching similar levels to greenfield projects. These challenges are also combined with a rapidly decreasing rate of new resource discoveries. Of the 239 copper deposits discovered between 1990 and 2023, only 14 have been discovered in the past decade. Greenfield copper projects are also particularly challenging, experiencing delays and facing long lead times (typically 17 years from discovery to production). Major copper projects including Oyu Tolgoi (Mongolia) and Quebrada Blanca 2 (Chile) have experienced significant delays and cost overruns.

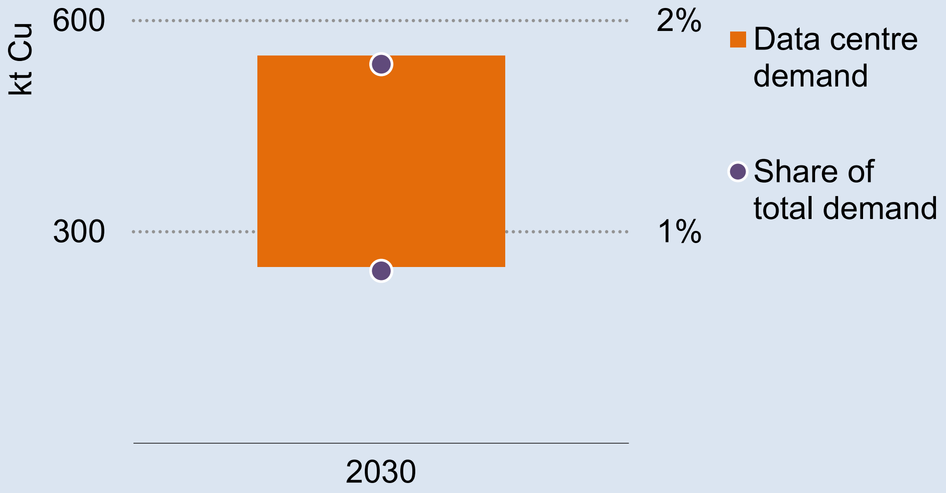
This underlines the significant challenge for copper supply security going forward. A wide variety of supply- and demand-side measures are needed to close the gap including stimulating investment in new mines, material efficiency, substitution and scaling up recycling. The lack of diversification for copper refining also presents supply security risks in the future.

Box 2.1 Copper for data centres and artificial intelligence

Artificial intelligence (AI) is emerging as one of the most consequential technologies in recent history. AI model training and use takes place in large data centres with both significant infrastructure and power requirements. Given their demand for electricity, copper is a critical component of both conventional and AI data centres due to its combination of high electrical and thermal conductivity, durability and affordability. In data centres, copper is primarily utilised in power distribution equipment, cooling systems and network infrastructure. The higher power requirements of AI server racks require more copper-intensive power distribution systems (power cables, busbars and electrical connectors), and also necessitate more copper-intensive advanced cooling infrastructure where copper is often utilised in heat exchangers. Copper is also used for some data transmission cables although there is an ongoing shift towards fibre optic cables for many applications.

With the exponential growth of AI applications, there is a concurrent rapid build-out of AI data centres across the world. There is a large degree of variation in estimates for the copper intensity of AI data centres with reported estimates varying by as much as 10 times. Our estimates show that copper use in data centres could range from 250 kt to 550 kt in 2030, equating to 1-2% of global copper demand, though this could be even higher depending on the speed at which demand for their services picks up.

Estimated copper demand in data centres in 2030 in the STEPS



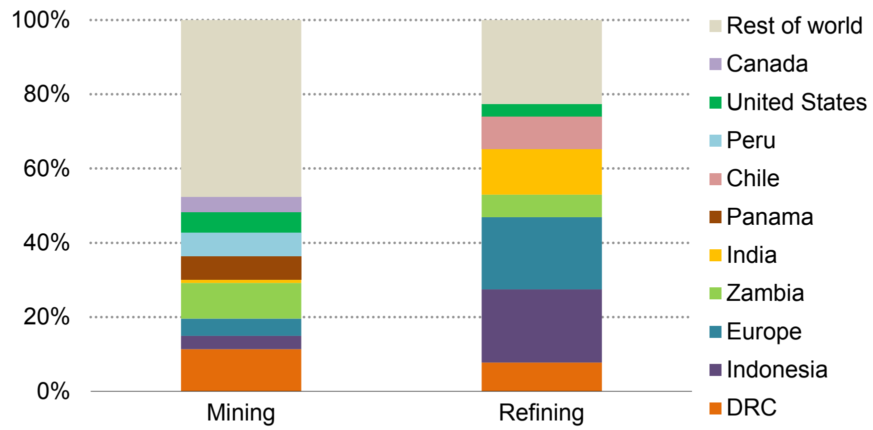
Notes: Includes both conventional and AI data centres.
Source: IEA (2025), Energy and AI.

Prospects for diversified supplies: A wide range of countries present diversification potential

Mined copper is relatively diversified compared with the other key energy minerals, but the declining ore grades and decreasing rate of new discoveries are driving supply concentration. Nevertheless, there are over 5.3 Mt of additional mining projects in diversified countries (outside the top supplier – Chile) in our base and high production cases planned by 2035. Five of the largest diversified suppliers by 2035 are the DRC, Zambia, Panama, Peru and the United States, which have a combined potential supply over 2 Mt. The DRC has a series of smaller projects planned as well as anticipated expansion of the Kamoa-Kakula project with over 600 kt of additions by 2035. Zambia also holds a large number of smaller planned projects with over 500 kt of additions by 2035. Panama holds one of the largest potential projects – the restart of Cobre Panama could provide almost 350 kt of supply alone by 2035. The United States also has 300 kt of smaller projects in the base and high production case planned by 2035; however, there are also some major early-stage potential projects beyond the cases such as the Resolution project, which could provide over 450 kt by 2035 if it goes ahead. The project faces legal challenges due to opposition from local Indigenous communities.

Copper refining is significantly more concentrated with China supplying almost half of global refined copper. Outside of China, there are almost 3.5 Mt of planned refining projects by 2035. The top five leading diversified refining suppliers by 2035 are Indonesia, Europe (primarily Sweden, Bulgaria, Spain and Germany), India, Chile and the DRC with over 2.2 Mt of collective capacity. However, many copper smelters closed in other regions due to environmental concerns and low margins, implying that reversing this trend comes with challenges. Moreover, China has built economies of scale, significant operational expertise and cost-competitiveness in copper refining, making it difficult for other smelters to compete.

Distribution of planned mining and refining projects outside the largest supplier



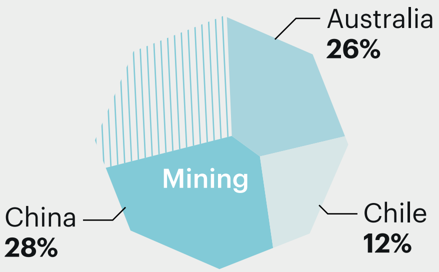
Notes: DRC = Democratic Republic of the Congo. Diversified mining and refining project additional volumes by 2035 in the base and high production cases excluding those of the top supplier (Chile for mining and China for refining).

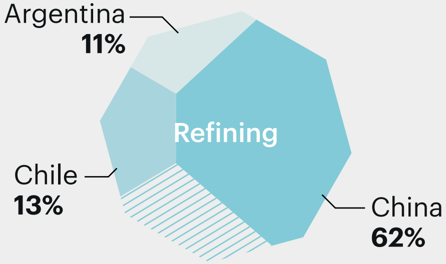
Outlook for lithium

Lithium

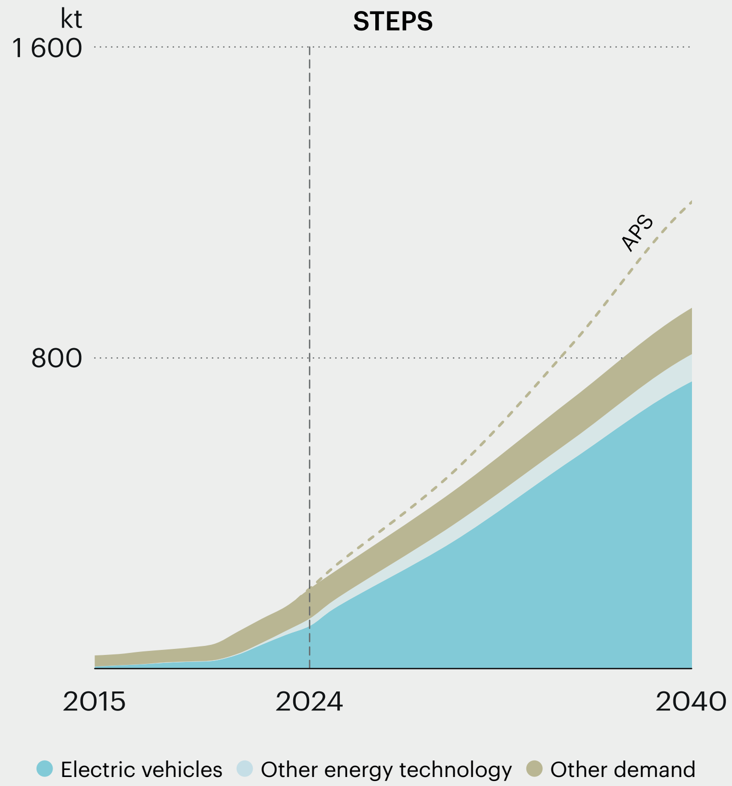
Li

Top three producers 2030

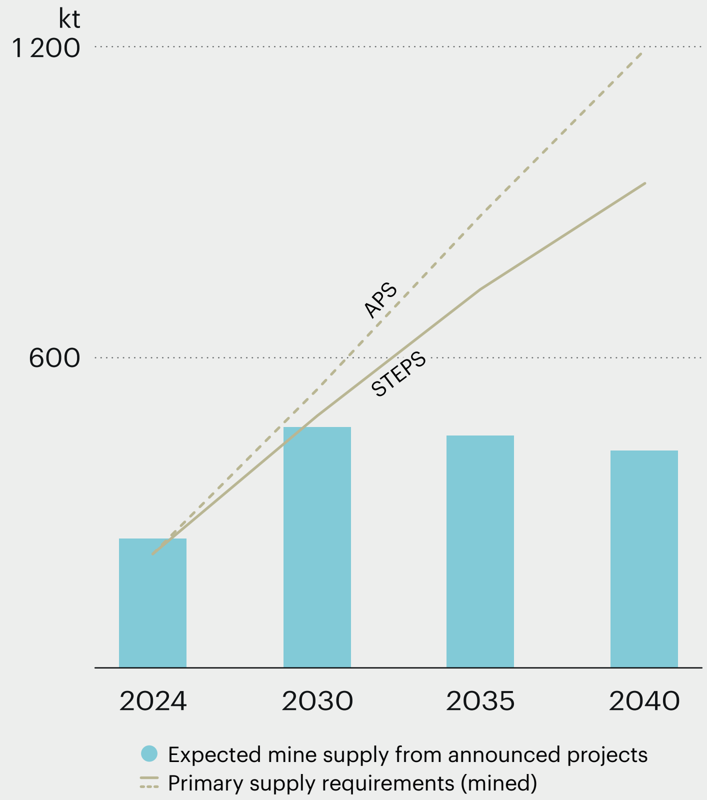




Demand outlook



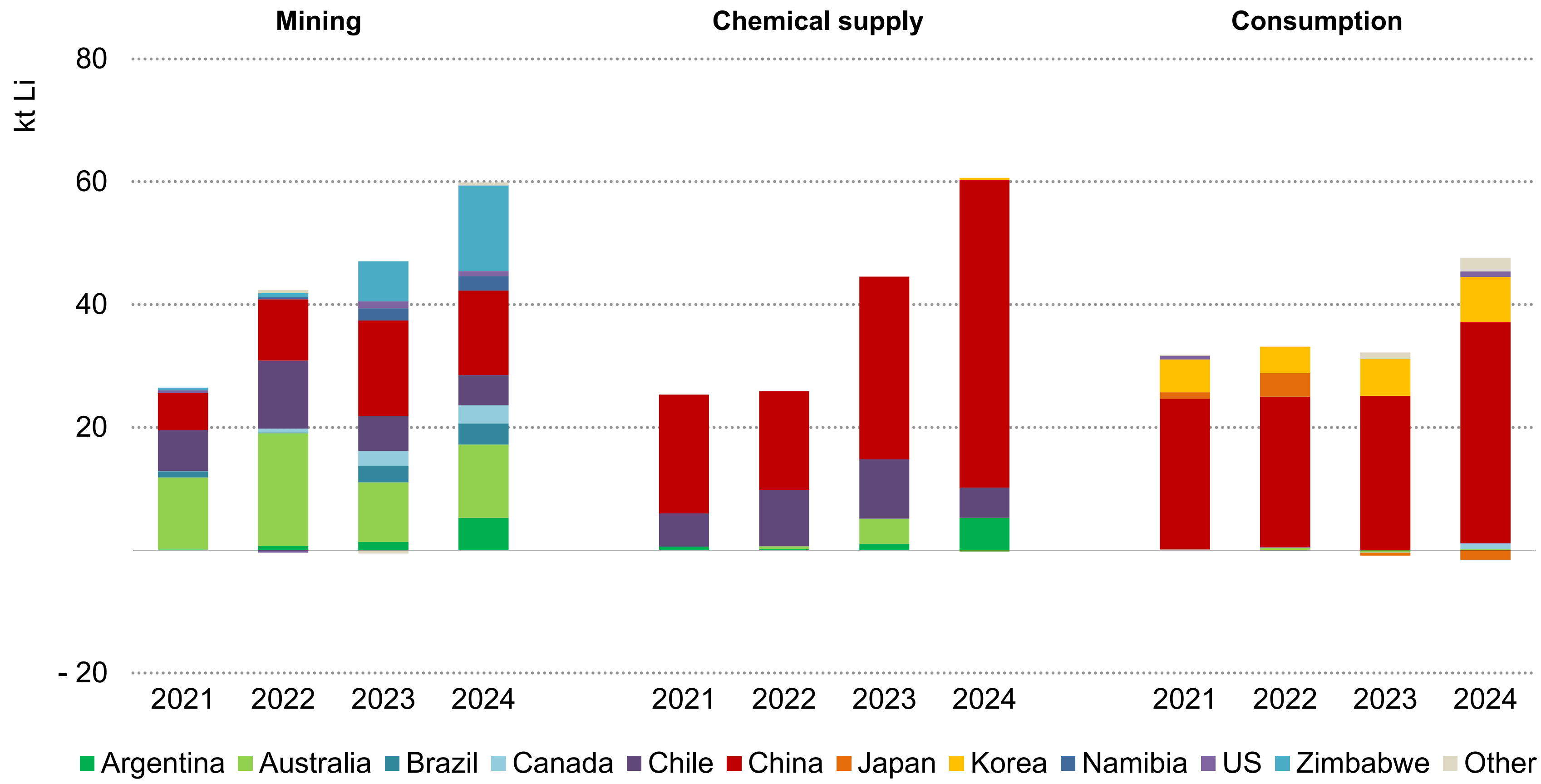
Mining requirements



STEPS	2021	2024	2030	2040
Cleantech demand (kt)	**38**	**128**	**369**	**809**
Other uses (kt)	57	77	87	119
Total demand (kt)	**95**	**205**	**455**	**928**
Secondary supply and reuse (kt)	2	7	16	82
Primary supply requirements (kt)	**100**	**198**	**439**	**844**
Share of top three mining countries	89%	77%	67%	69%
Share of top three refining countries	99%	96%	85%	85%

Recent market developments: remarkable supply growth as mines ramp up in new regions, but refining remains concentrated

Annual change in lithium mining, chemical supply and consumption by region



Recent market developments: Strong demand growth outweighed by even faster supply growth

Lithium demand saw strong growth in 2024, but supply even more so. After a period of significant volatility, lithium prices have now stabilised. Lithium demand expanded by 30% year-on-year, reaching over 200 kt lithium content (Li), or about 1.1 Mt in lithium carbonate equivalent (LCE). This increase is the equivalent of global lithium demand in 2018. The bulk of lithium demand growth came from the EV sector, but energy storage, currently 9% of lithium demand, is showing rapid growth. China represents over three-quarters of global lithium demand, followed by Korea and Japan, notably due to their strong battery cathode manufacturing capacities. The rise of LFP chemistries in EV batteries drove most of the additional demand towards lithium carbonate, while lithium hydroxide, used primarily in nickel-rich cathodes, experienced smaller growth.

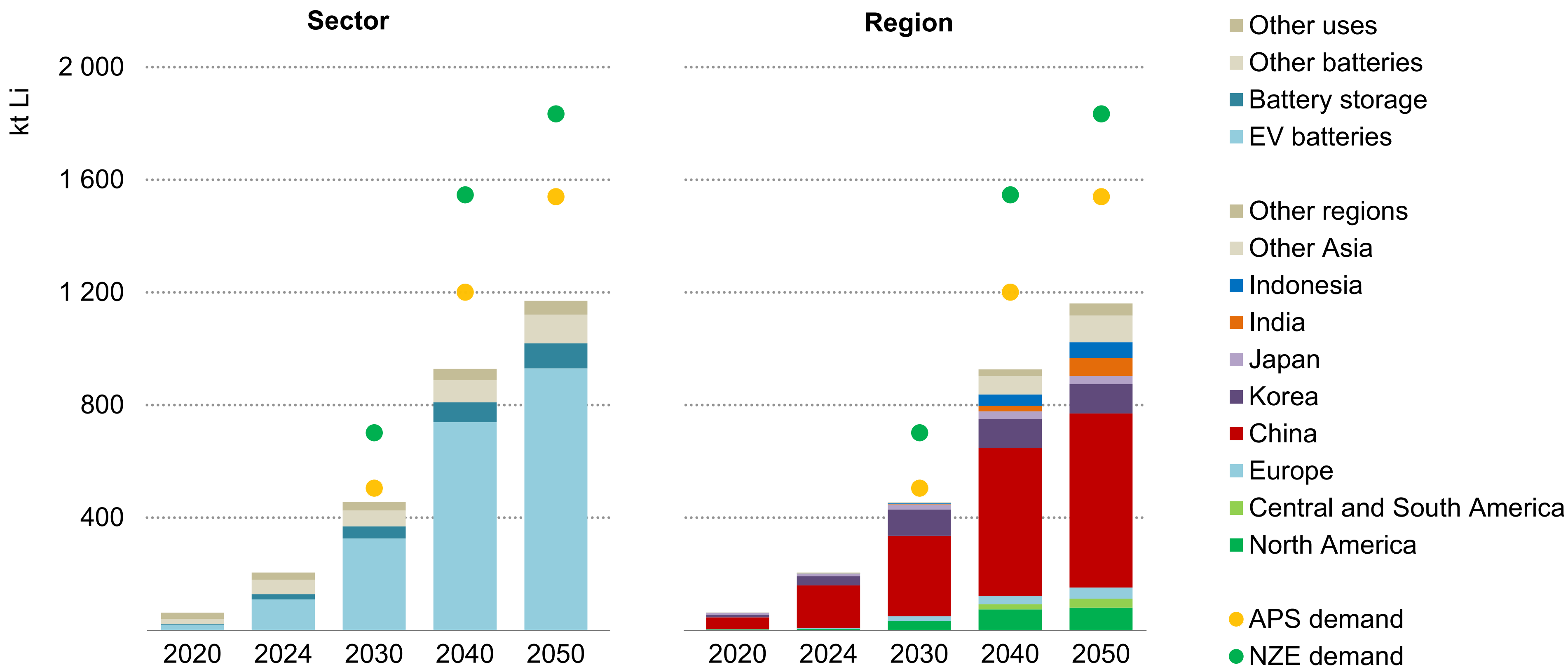
Global lithium production increased by over 35% in 2024, further tilting the market towards oversupply. This pushed lithium prices down to USD 12 000 per tonne of LCE, well below the peaks reached in 2022. Compared with 2022, the cost of lithium in a typical 57 kWh average-size battery fell from USD 67 to USD 15 today, significantly easing manufacturers' material bill. Lower price levels also triggered the industry's consolidation efforts, with several large-scale mergers and acquisitions taking place. For example, Rio Tinto acquired Arcadium Lithium, which had itself merged from two major lithium players – Livent and Allkem.

While much of the additional supply in 2024 came from leading producers such as China and Australia, approximately 30% of new output originated from Africa, particularly Zimbabwe and Namibia. This is a significant shift, given that Africa accounted for just 6% of global lithium mining in 2023. In Latin America, Argentina and Brazil saw a 65% surge in lithium output. Eramet's Centenario project in Argentina began small-scale production, raising hopes for an industrial breakthrough in direct lithium extraction (DLE) and unlocking new brine resources. However, the low-price environment also led to closures of several Australian operations and the cancellation of projects in diversified regions.

On the refining side, China remains the dominant supplier, producing 70% of global lithium chemicals. In December 2024, China announced it was considering adding lithium refining technology to its "dual use" export control list although some refining capacity has recently been built outside China, notably in Australia with its Kwinana and Kemerton plants. Several refineries and converters in diversified areas ramped up production in 2024, albeit with small volumes – in the United States (Bessemer City), Korea (Gwangyang), Japan (Naraha), Indonesia (Sulawesi) and Germany (Bitterfeld), as well as the Kokkola project in Finland under construction.

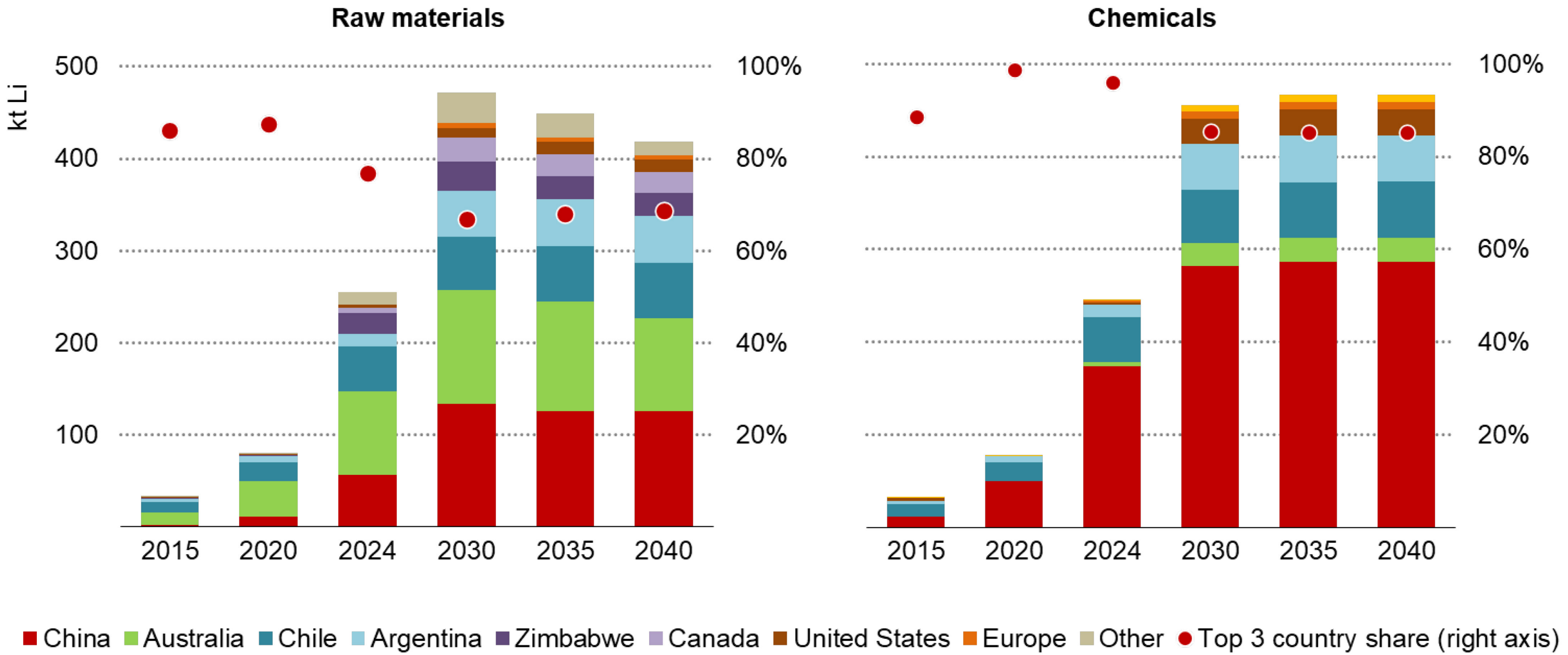
Demand: EV and storage batteries dominate lithium consumption; consumer geography diversifies

Global lithium demand outlook by sector and region in the STEPS



Supply: New lithium extraction activities emerge in a number of regions; China continues to dominate refining of hard rock ore

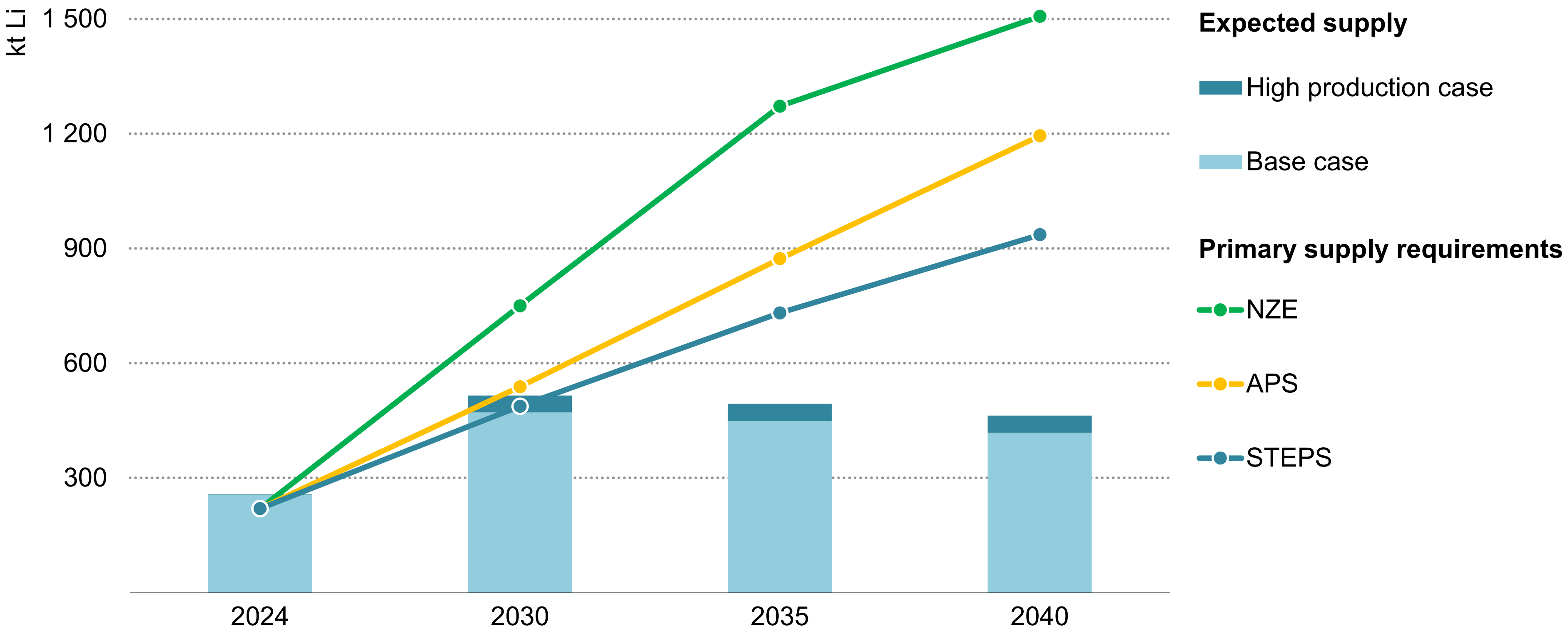
Lithium production from operating and announced projects in the base case



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.

Market balances: The lithium market is expected to remain well-supplied in the near term, but additional mining projects will be needed to meet continued demand growth in the years ahead

Mined lithium 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 the Overview section for definitions of the base and high production cases.

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Market outlook

Demand

While lithium was traditionally used in applications such as ceramics, lubricants and pharmaceuticals, the rapid expansion of the battery market for EVs and energy storage has made battery applications the overwhelmingly dominant use of lithium across all scenarios. Lithium's unique properties make it an essential material for battery cathodes and electrolytes. If prices remain stable and industrial-scale production continues to expand, short-term incentives for substituting lithium might be weakened, reinforcing lithium's role in the EV sector.

In the STEPS, annual lithium demand reaches 700 kt Li by 2035 (3 700 in LCE), up from around 205 kt Li today and just 60 kt Li in 2020. Lithium demand has already tripled since 2020, and is expected to see another tripling over the next decade. The EV sector accounts for 90% of this additional demand. Furthermore, as global investment in battery storage triples by 2030, energy storage begins to drive significant growth in lithium demand. The electrification of the energy system accounts for 95% of additional lithium demand between today and 2035. In the STEPS, lithium demand is projected to reach 1 160 kt Li by 2050 (over 6 000 kt LCE). The APS sees a 30% higher demand in 2050, with an additional 20% increase in the NZE Scenario.

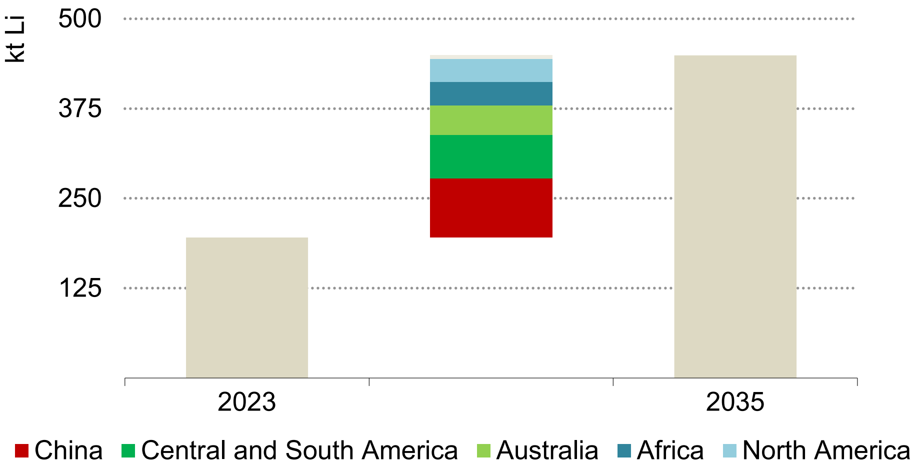
Lithium consumption is currently dominated by China, around three-quarters, followed by Japan and Korea, which also host significant cathode manufacturing capacities. These regions drive a significant share of future demand growth in the near future. From 2030 onwards, consumption expands to new regions, in the United States and in the European Union, but also in other Asian nations, including Indonesia and India, as they nurture the battery manufacturing supply chains.

Mining

On the mining front, the current project pipeline appears on track to double production by 2030. This expansion is underpinned by an increase in the median size of mine output from 1 900 tonnes Li to approximately 2 700 tonnes Li. However, sustaining demand growth post-2030 would require the addition of further projects.

Announced mining projects indicate some degree of geographical diversification on the horizon. The top three mining producers represented 77% of global supply in 2024, but this share falls to 67% by 2030. Additional supplies come from Africa, notably Zimbabwe and Mali. Production in North America quadruples by 2030, with Moblan and Whabouchi mine projects in Canada and Thacker Pass in the United States. In Central and South America, while supply is currently dominated by Chile, 70% of additional supplies is expected to come from Argentina.

Geographical distribution of lithium raw material supply growth between 2023 and 2030



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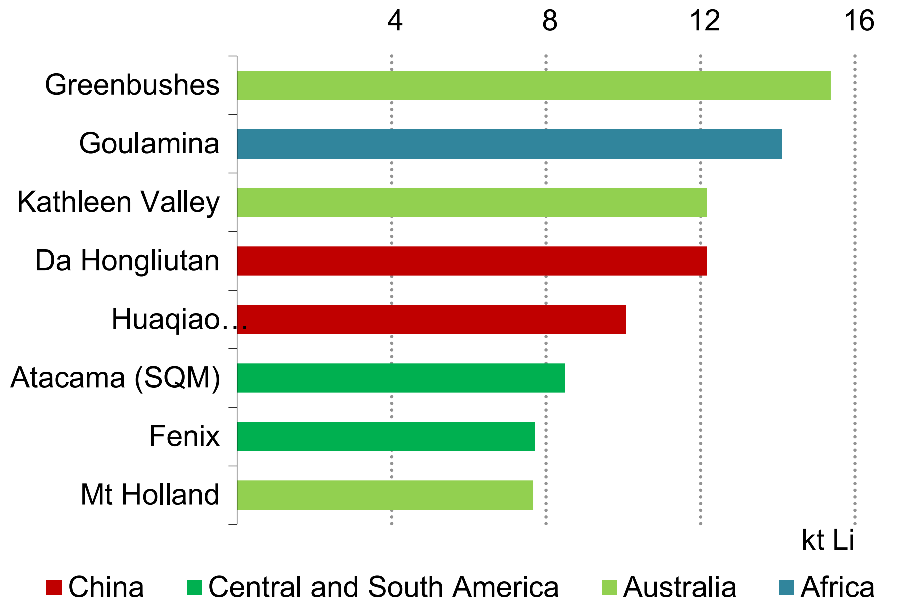
However, the largest new projects and extensions are often driven by the incumbent producers: from Mount Holland, Kathleen Valley and Greenbushes mines in Australia, and Huaqiao and Da Hongliutan mines in China. Australian projects may act as swing producers, with their spodumene output ramped up quickly during price surges. While some projects are now under care and maintenance due to falling prices, production could be revived if downstream demand resurfaces. Accounting for project ownership offers a slightly different perspective on geographic diversification, considering that many African projects are being operated by Chinese companies, including the large-scale Goulamina project in Mali.

Key projects driving lithium mining supply growth, 2024-2030



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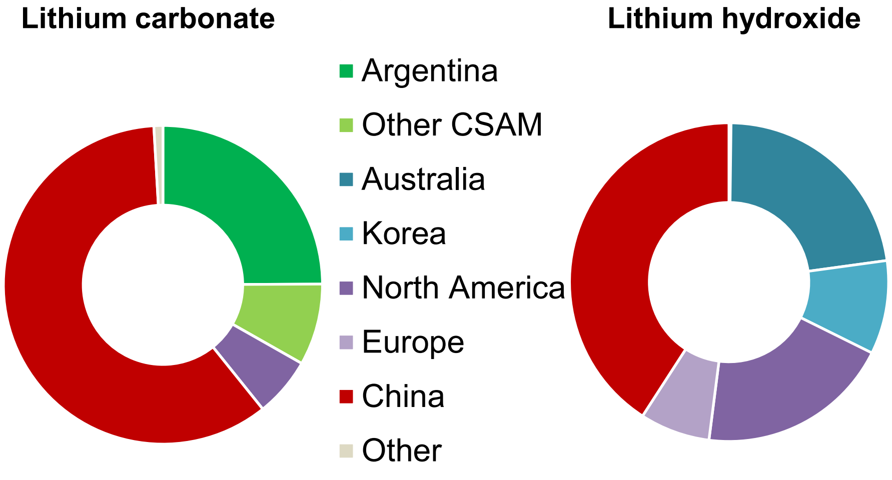
Refining and chemical supply outlook

For lithium chemicals, there are a large number of projects in the pipeline to process projected mine production. However, lithium refining is subject to a stronger geographic concentration, with three-quarters of additional supplies between 2024 and 2035 coming from just three countries. Lithium-rich brines, which account for about a third of global supply, are typically processed into usable chemicals near their extraction sites, primarily in China, Chile and Argentina, meaning that the distribution of these chemical supplies is largely dictated by geography. In contrast, the remaining two-thirds of lithium chemical production comes from hard rock ores, which are mined and then exported overseas for processing. While China extracts only 22% of the world's lithium resources, it refines 70% of global lithium chemicals and controls 95% of the refining for hard rock ores.

Geographical distribution of planned additional lithium chemical projects, 2024-2035



Note: CSAM = Central and South America.

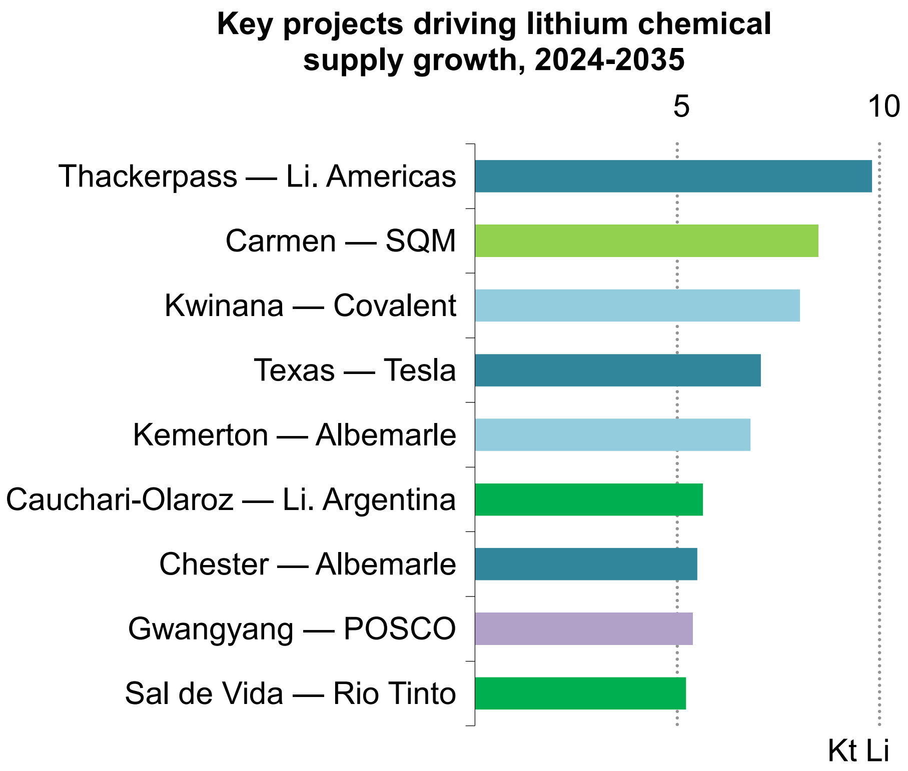
The lithium market is splitting into two distinct supply chains: lithium carbonate, favoured for LFP batteries, and lithium hydroxide, essential for nickel-rich batteries. China remains the largest source of growth for both carbonate and hydroxide production between 2024 and 2035. Lithium carbonate is also seeing production expansions in Central and South America, while expansions for hydroxide are increasingly driven by new refining projects in Japan, Korea, Europe, and North America. This divergence reflects current preferences for battery chemistries, and leaves tasks to deal with market uncertainties. If LFP gains traction beyond China, hydroxide investments may struggle. Conversely, a sustained preference for nickel-rich chemistries could leave carbonate producers at a disadvantage. Whether today's refinery plans align with tomorrow's markets remains an open question.

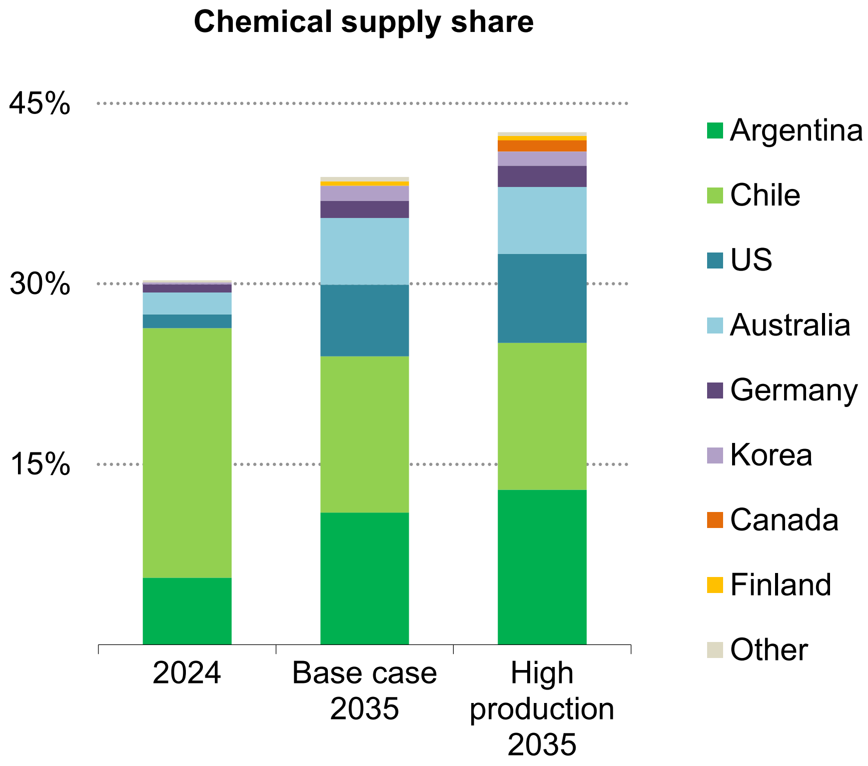
Market balances

In the STEPS, assuming all base case projects proceed as planned, supply is expected to stay above primary demand until the late 2020s, after which market balances shift. An estimated 55 additional average-sized mines would be required to meet demand in 2035. In the APS, market balances remain surplus for a few years, but project development would need to accelerate more rapidly to keep pace with growing demand, with even greater needs in the NZE Scenario.

Prospects for diversified supplies: Planned refinery projects in the base case could bring up the share of ex-China producers from 30% to 40% by 2035

Lithium chemical supply outside top producer country





Notes: Select projects are those providing the largest supply additions to the market between today and 2035, excluding projects located or whose main owner is a company headquartered in the top producer.

Prospects for diversified supplies: Key projects

In the base case, the top supplier's share of lithium chemical supply declines from 70% to 60% by 2035, with the potential for further reductions if additional projects in diversified regions materialise. Lithium brines contribute to this shift, driven by expansions in Chile and new projects in Argentina. However, significant challenges persist in diversifying the refining of hard rock ores.

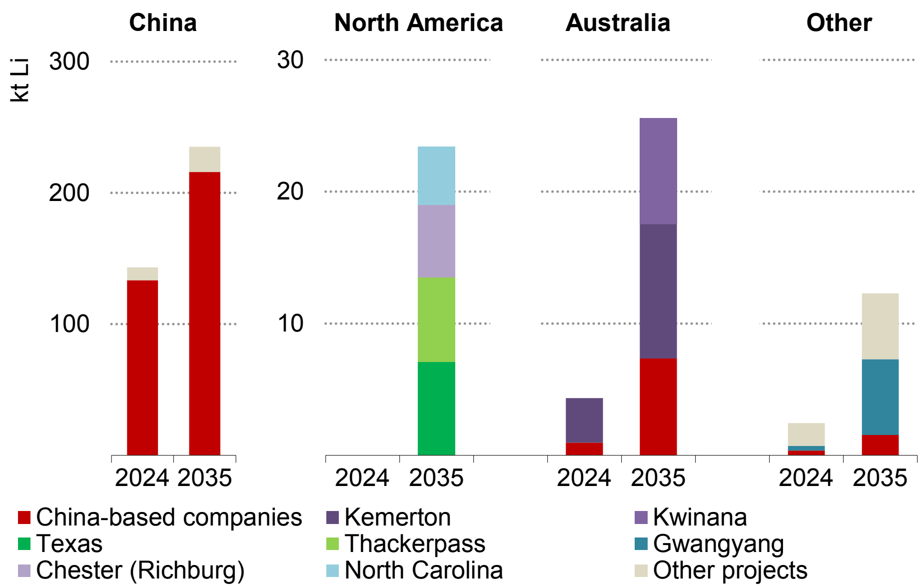
Addressing the bottleneck in hard rock ore refining is crucial for enhancing supply resilience. While lithium hard rock mining is expanding across multiple nations, 95% of mine concentrate processing still takes place in a single country, China.

A handful of key planned projects could shift this dynamic, potentially enabling a tenfold increase in hard rock refining capacity from today's small levels. This includes expansions at Australia's Kemerton plant and the development of the Kwinana facility. In North America, domestic refining capacity is set to grow with projects such as Tesla's Texas refinery, Piedmont's North Carolina plant and Albemarle's Chester facility. Beyond these, Posco's Gwangyang plant is a notable development in Asia. In Europe, hard rock refining projects remain limited, but the recently opened Kokkola plant in Finland marks a step towards diversification.

Non-conventional deposits: Sedimentary clay

Additional supplies could be unlocked through several refinery projects utilising lithium sedimentary clay deposits. These include the Thacker Pass project in the United States, Jadar in Serbia, and Sonora in Mexico. However, refining these less conventional geological deposits carries industrial risks that need to be managed.

Prospects for lithium hard rock refining by region



Additional projects in Europe?

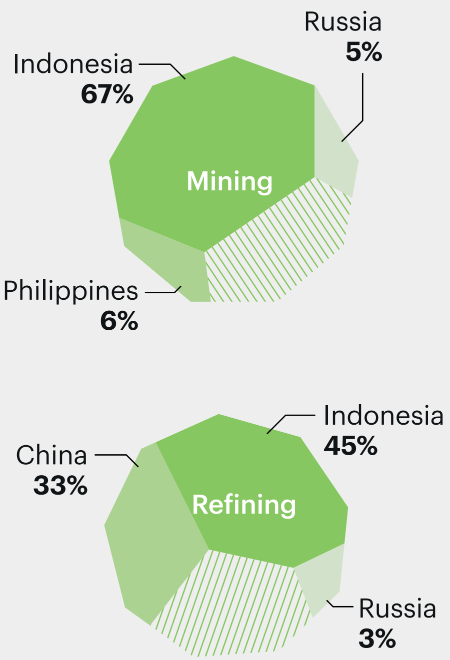
Beyond the most probable German and Finnish lithium projects, an additional set of strategic projects identified by the European Commission could further expand the European lithium pipeline. These include three integrated projects encompassing both mining and refining: two in France (one targeting hard rock, the other brine), and one in the Czech Republic, as well as mining and refining developments in Spain and Portugal. However, the direct consumer pool, particularly European lithium battery chemical producer projects, precursor cathode material (pCAM) and cathode material, may still be insufficient to absorb much of the production from these potential projects.

Outlook for nickel

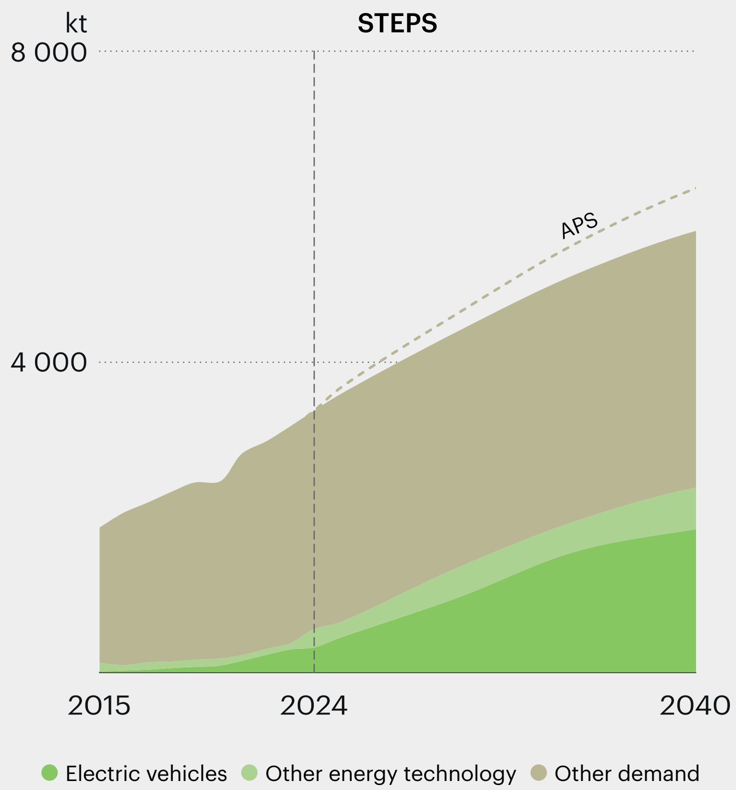
Nickel

Ni

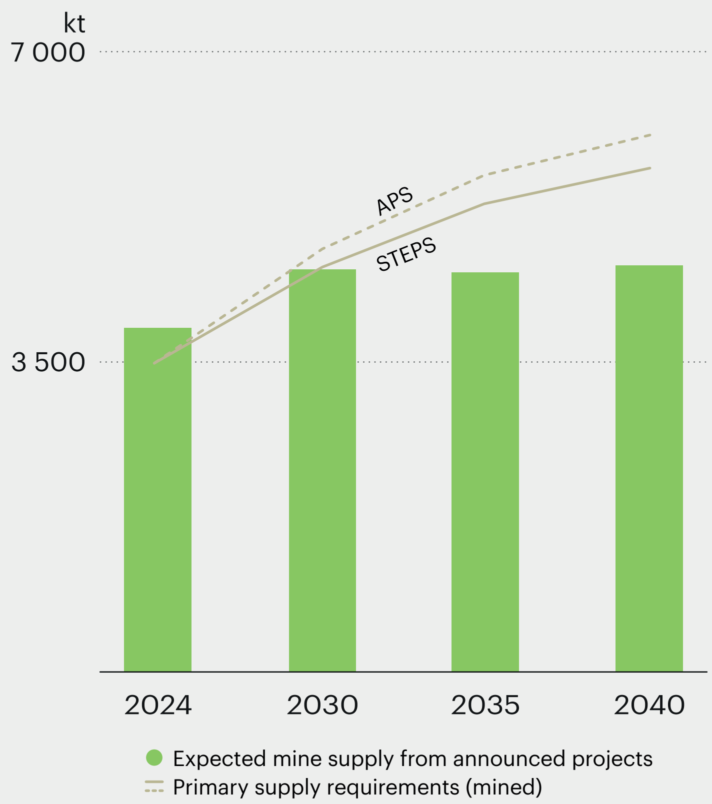
Top three producers 2030



Demand outlook



Mining requirements



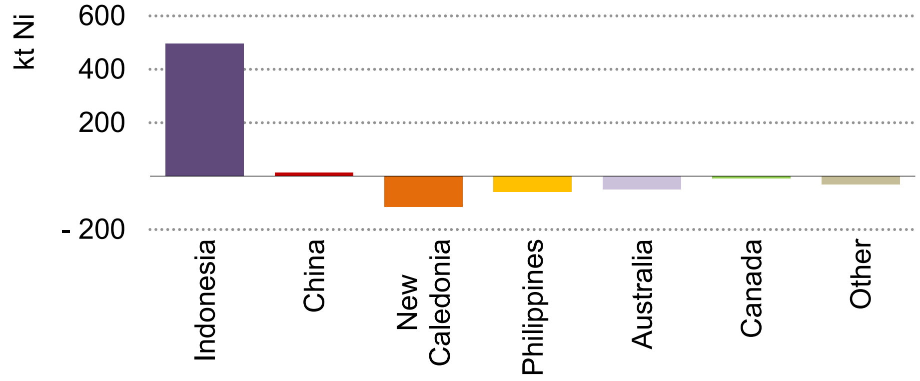
STEPS	**2021**	**2024**	**2030**	**2040**
Cleantech demand (kt)	**226**	**562**	**1 349**	**2 381**
Other uses (kt)	2 600	2 809	3 039	3 304
Total demand (kt)	**2 825**	**3 371**	**4 389**	**5 685**
Secondary supply and reuse (kt)	25	62	63	295
Primary supply requirements (kt)	**2 709**	**3 484**	**4 326**	**5 382**
Share of top three mining countries	64%	77%	78%	84%
Share of top three refining countries	66%	78%	81%	83%

Recent market developments: Today's oversupplied market, driven by increasing Indonesian nickel supply, masks longer-term threats to nickel output

In 2024, nickel prices rallied in the first half of the year, rising by almost 20% on expectations of constrained global supply and a shrinking supply surplus. However, in the second half of 2024, prices reversed course and ended the year nearly 30% lower than the average price in 2023. Nickel prices remained subdued in early 2025. Several factors contributed to the downturn in late 2024, including the faster adoption of LFP chemistries and persistent downstream inventory overhang. Nevertheless, the primary driver continued to be oversupply, driven largely by high production volumes from Indonesia.

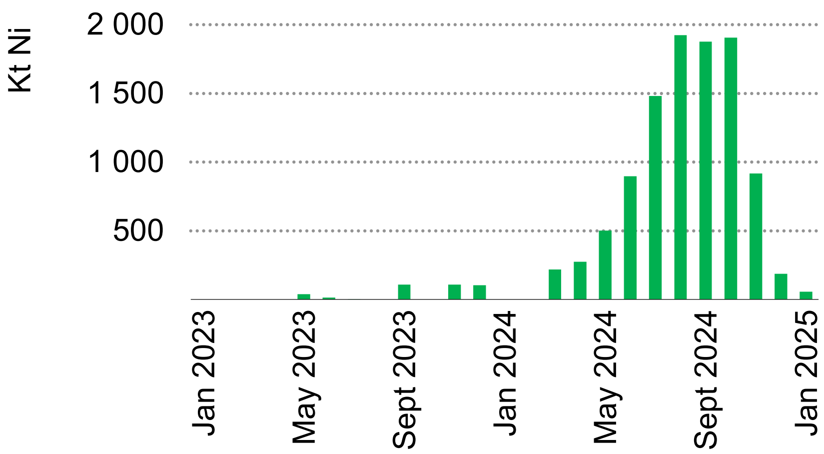
Global mined nickel supply increased from 2023 to 2024 by just under 10% from 3.6 Mt to 3.9 Mt, largely driven by Indonesia, which saw a 25% increase in output. This was offset by declines in other regions such as New Caledonia, Australia, Canada and the Philippines, which saw a 25% decrease in production year-on-year. Despite the increases in Indonesian mined supply, there are growing signs of a slowdown in the pace of output growth. This follows recognition that the country's pace of smelter investment may deplete its high-quality nickel ore reserves within the next few years, despite holding the world's largest nickel reserves and resources at 55 Mt, more than double the second-largest holder, Australia, at 24 Mt.

Change in mined nickel supply from 2023 to 2024



The combination of low prices and concerns around diminishing ore quality have prompted the country to issue a mining production quota of close to 200 Mt, lower than in previous years. This has also begun to affect Indonesia's midstream production, as major producers have started cutting nickel pig iron production – a precursor for stainless steel, mixed sulphide precipitate (MSP) and matte, which can be further processed to battery-grade nickel. In an effort to conserve higher-grade reserves and ease pressure on the midstream industry, the Indonesian government introduced a long-discussed moratorium on new rotary kiln electric furnace processing plants in August 2024. In March 2025, the government also announced plans to progressively increase royalty rates for nickel ore and introduce ones for nickel matte and ferronickel, which could affect miners and smelters with higher-cost profiles.

Imports of nickel ore from the Philippines to Indonesia



Source: National Export Import Data, BPS-Statistics Indonesia (2025).

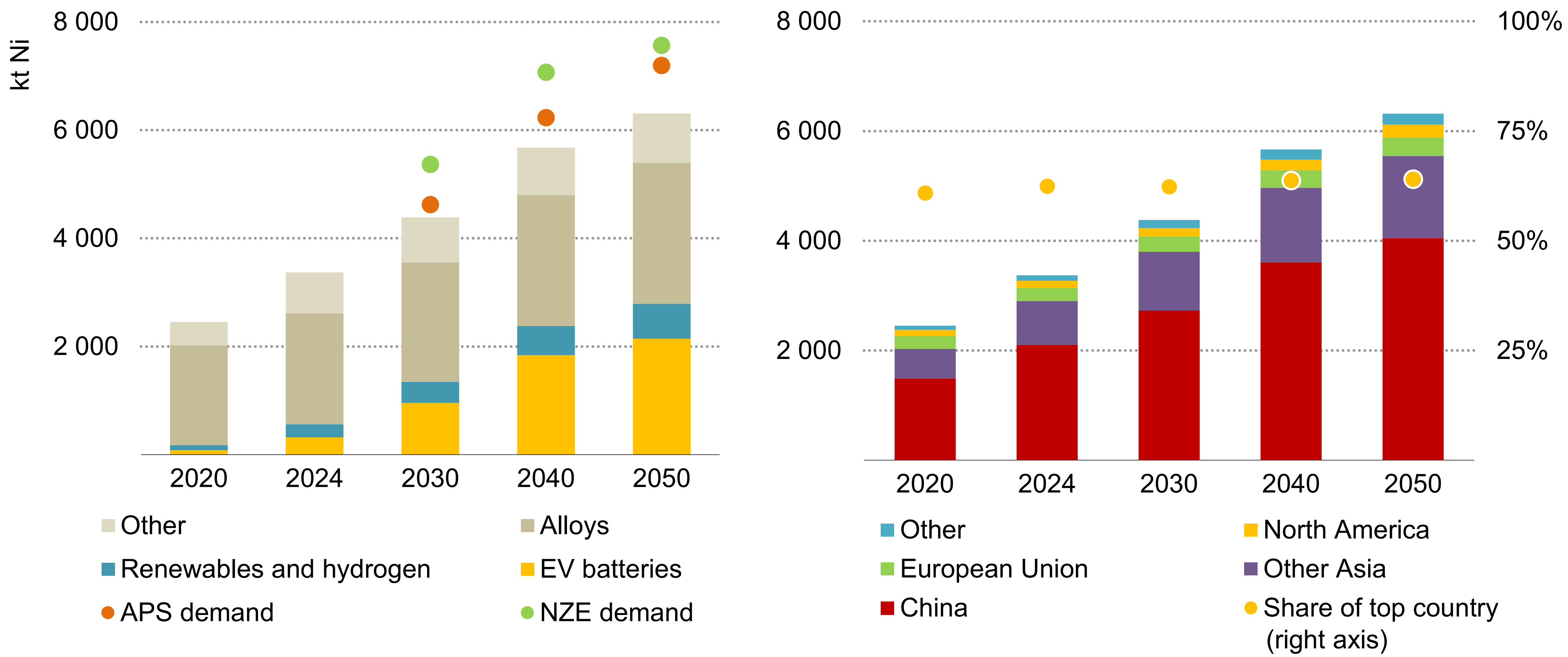
In response to this environment, smelters and refineries in Indonesia have started to look elsewhere for feedstock supply, with the average monthly raw ore import from the Philippines significantly increasing from 2023 to 2024. The renewed interest in the Philippines' ore has led officials to revisit a possible export ban on raw ore, which is a measure that has been discussed at various times over the years. However, simultaneously, one province within the country announced a potential ban on new mining permits, which could constrain the development of the industry in the country and further limit ability to meet midstream demand.

Elsewhere, persistently low prices from 2023 through early 2025 triggered several announcements of mine and processing plant closures, pauses, production downgrades and cancellations. This was most evident in higher-cost regions such as New Caledonia, Australia and Canada, where shutdowns, closures or reduced output put around 500 kt of mined supply and 300 kt of refined supply at risk.

In early 2024, the Western Australian government introduced a Nickel Financial Assistance Programme to support the struggling industry in the face of low prices. The initiative provides a 50% royalty rebate for 18 months when prices fall below USD 20 000 per tonne, with repayment due over the following 24 months. Around the same time, the federal government placed nickel on its critical minerals list, unlocking access to AUD 4 billion (Australian dollars) under the Critical Minerals Facility and additional support from programmes such as the International Partnerships programme (AUD 40 million).

Demand: Growth in nickel demand is driven by energy applications, with China as the largest consumer of primary nickel, followed by Indonesia

Global nickel demand outlook by sector and region in the STEPS



Note: Alloys include demand for both 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

Historically, demand for nickel was primarily for its use in alloys for stainless steel and non-ferrous applications, capturing 75% of nickel's total demand in 2020. Recent years have seen a shift in demand composition towards energy technologies, given nickel's use in nickel-rich batteries and renewables such as wind and geothermal. In 2024, energy technologies made up almost 20% of nickel's total demand, which is projected to rise to just over 40% by 2040 in the STEPS and over 50% in both the APS and the NZE Scenario.

Global nickel demand rose by 6% in 2024 to 3.4 Mt. Most of this growth came from the use of nickel in energy technologies, such as EV batteries and renewables. Across all scenarios, demand growth continues to be driven by clean energy technologies. In the STEPS, total nickel demand rises to just over 5.5 Mt by 2040. In the APS and the NZE Scenario, a faster ramp-up of EV sales and the more rapid deployment of renewables and hydrogen technologies push nickel demand higher, surpassing 5.5 Mt by 2035.

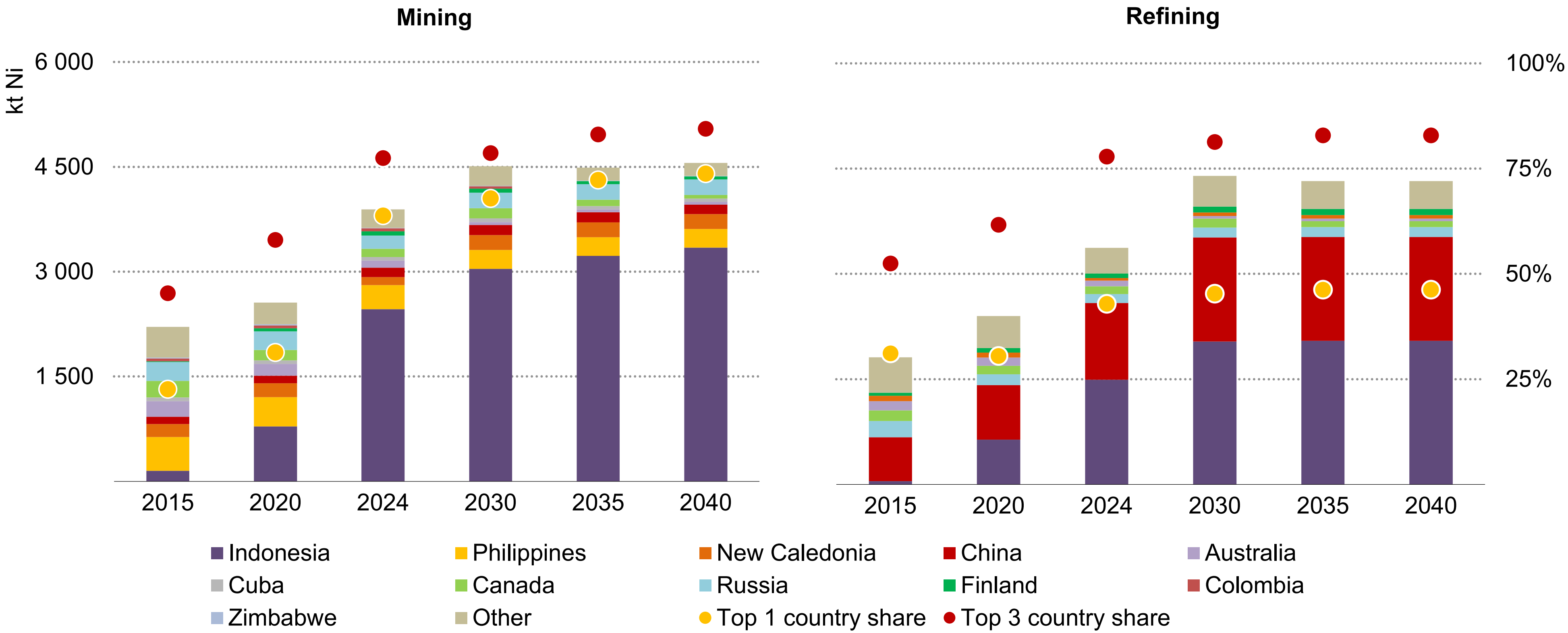
Changing battery technology trends in favour of LFP chemistries has pushed projected nickel demand slightly lower than last year's Outlook. Nevertheless, nickel-rich chemistries are expected to remain a major part of EV batteries given their competitive advantage for battery makers outside China, and North American and European consumer preferences for long-range vehicles.

Regionally, China has been the largest consumer of nickel, accounting for an average 60% of global demand from 2020 to 2024, primarily for stainless steel production. However, China's battery-related nickel consumption is also set to rise substantially, growing from 200 kt to over 1 300 kt by 2040. Indonesia follows as the second-largest consumer, accounting for 5% of the market in 2024, with all of its demand growth in the last ten years linked to stainless steel production. Other key consumers include the United States, which has accounted for 5% of global demand over the past decade, as well as countries in the European Union, including Germany, Italy, Spain and Belgium, and Russia.

Looking ahead, China continues to dominate nickel consumption, with consumption for stainless steel production remaining the leading driver until around 2040, when demand for other applications surpasses stainless steel consumption. Precursors for EV batteries and energy storage drive this, but growth also occurs in non-ferrous alloys and plating uses. Indonesia's nickel consumption growth is more muted, remaining largely concentrated in stainless steel production.

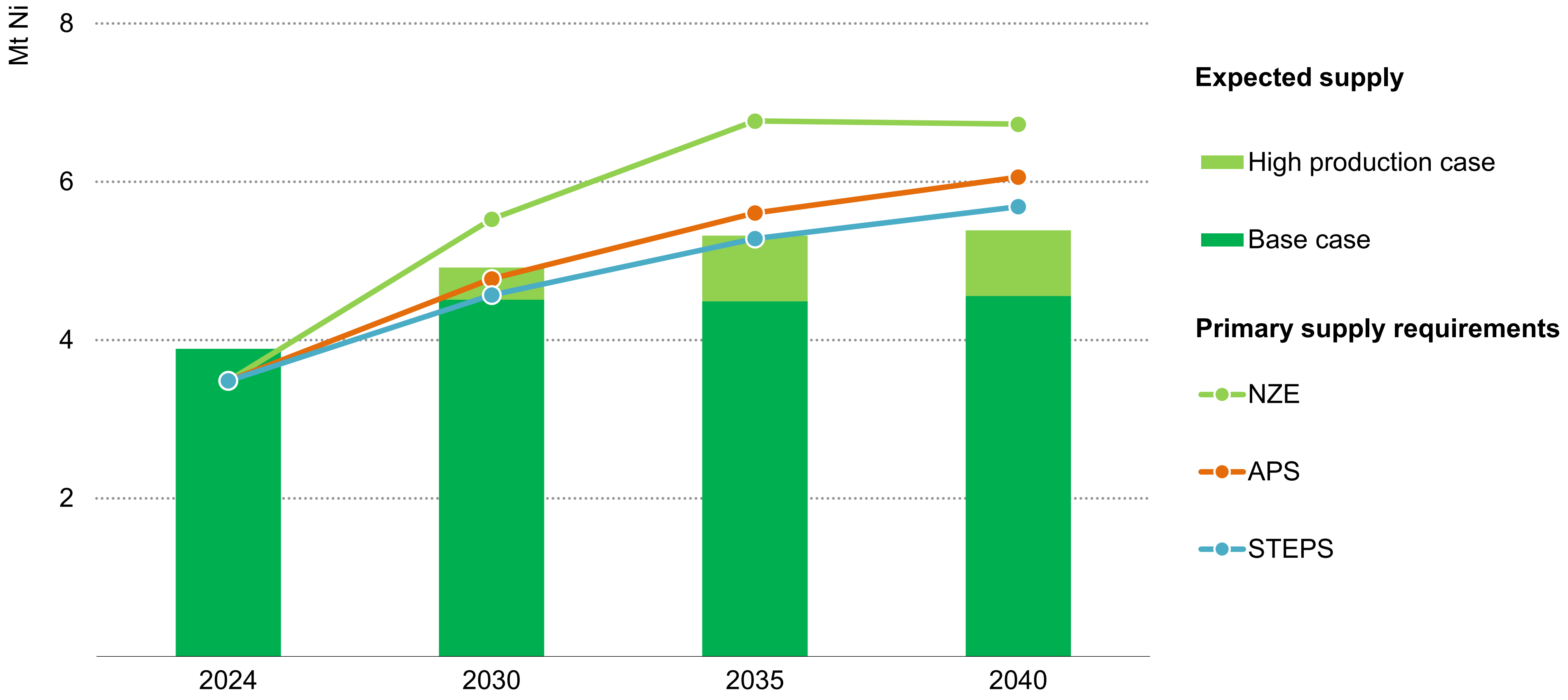
Supply: Geographical concentration for mining and refining increases as projects in diversified regions are impacted by low prices

Nickel production from operating and announced projects in the base case



Supply: There is a near-term supply surplus, which dissipates after 2030 as demand continues to grow

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 Overview section for definitions of the base and high production cases.

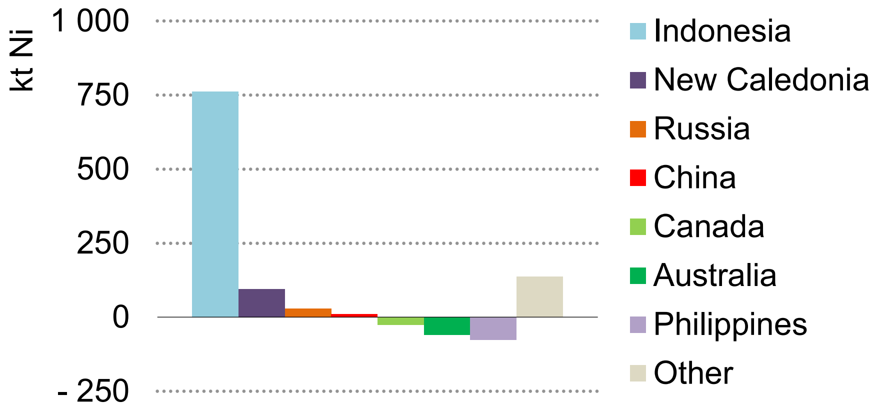
Supply: Indonesia's production of refined nickel continued to outpace growth in China, solidifying its market dominance in the nickel supply chain

Mining

Indonesia maintained its dominance in mined nickel supply in 2024, representing over 60% of global production. Since 2015, its output has increased by 16 times, primarily through laterite ore production. Laterite ore, also produced in Australia, New Caledonia and the Philippines, has traditionally fed ferronickel and nickel pig iron for stainless steel production. However, between 2023 and 2024, output fell by 14% in the Philippines and 50% in New Caledonia. In contrast, higher-grade sulphide ores, historically the main source for nickel sulphate, are concentrated in Australia, Canada, China and Russia. Australia and Canada recorded production declines in 2024 while Finland saw an increase.

Indonesia's nickel ore output is expected to continue growing, rising by 25% to reach 3 Mt by 2030, followed by a slower 10% increase to 2040. Although the country's reserves expanded by over 60% to 55 Mt in 2024, concerns over resource depletion are expected to limit major growth beyond 2040. Nonetheless, Indonesia remains the dominant player, accounting for around 75% of global supply by 2040. In the base case to 2035, New Caledonia is the only other major producer outside the top three to see output growth, as some previously curtailed projects restart. Meanwhile, Canada, Australia and the Philippines see production declines as low prices trigger project cancellations or scaling back.

Change in mined nickel supply from 2024 to 2035 in base case



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Refining

Indonesia's production of refined nickel continued to outpace growth in China in 2024, with output rising by almost 10% year-over-year to 1.5 Mt. The country continues to grow its refining capabilities, growing to almost 40% to 2030 and further widening gaps with the second-largest refiner, China. This growth largely stems from the production of ferronickel and nickel pig iron, which can be further refined into matte for use in battery-grade nickel sulphate. The country also produces significant quantities of MSP and mixed hydroxide precipitate, both intermediate steps towards battery-grade nickel sulphate.

Meanwhile, after a substantial 70% increase from 2015 to 2023, China's nickel industry growth has begun to plateau, with only a 35% rise through 2040 in base case. Nonetheless, China remains the dominant supplier of final nickel chemicals, including nickel sulphate, a key component for EV battery precursor materials. The country accounted for 60% of global nickel chemical production in 2024 and retains its high share through 2040. However, Indonesia is set to see a 3.5-fold increase in nickel chemical production between 2024 and 2040, in line with its long-term industrial policy goals to capture more of the value chain.

The increase in geographic concentration in refining is even more stark than in mining compared with the last year's Outlook. The top three countries' share of refined nickel in 2030 is up by 2 percentage points, from 76% to 78%. Indonesia's share alone rose by 5 percentage points, from 62% to 67% in 2030, while Japan, Australia and Canada saw downwards revisions in their projected refined nickel output.

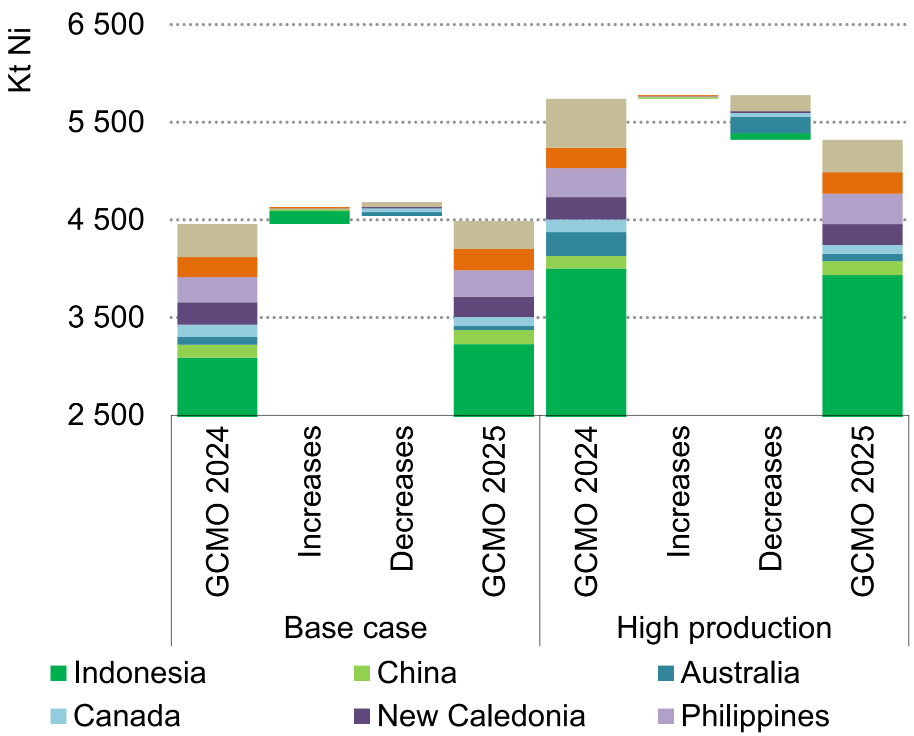
The share of secondary supply in total nickel demand (excluding direct-use scrap) was about 2% in 2024. A combination of policy actions that incentivise higher recycling of EV batteries means that this share grows to 5% by 2040 in the STEPS.

Market balances

In the near term, the nickel market is likely to remain in surplus under both the STEP and APS, driven largely by high investment in recent years, especially in Indonesia. However, with lower supply projections this year, the surplus disappears after 2030 in the base case supply scenario.

Relative to last year's Outlook, upward revisions in projected production in Indonesia, Russia and China to 2035 are offset by downward revisions in Australia, Canada, the Philippines and New Caledonia, resulting in similar total supply in 2035. However, our high production case has undergone a notable downwards revision due to the prevailing price environment. As several projects were delayed, scaled back or cancelled, 2035 supply is now expected to be 10% lower than last year's projections. This decrease was largely among non-leading producers, but is also seen in Indonesia. Australia sees the largest downwards revision in projected 2035 supply.

Change in 2035 mined supply between GCMO 2024 and GCMO 2025



Notes: GCMO = Global Critical Minerals Outlook. GCMO 2024 refers to last year's production projections whereas GCMO 2025 considers this year's projection results.

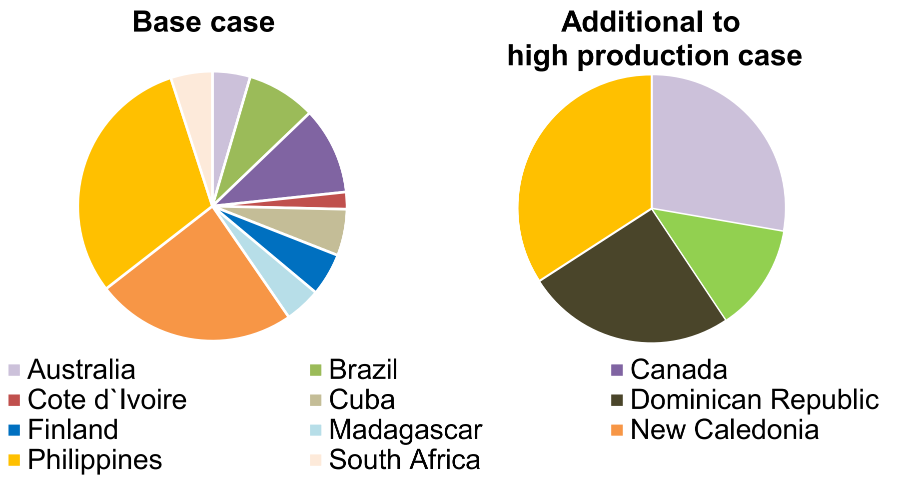
Prospects for diversified supply: Many projects exist that could improve the diversification of nickel supply, but strengthened policy support would be required

Several nickel mining projects in geographically diverse regions, such as Australia, Brazil, the Dominican Republic and the Philippines, are present in the base case and high production case. In the base case, just over half of this supply is in the Philippines and New Caledonia in 2035. Looking at additional supply that comes online in the high production case, the Philippines leads with the largest additional supply, followed by Australia, the Dominican Republic and Brazil. There are also mining projects that could potentially be reopened or restarted, particularly in Australia, Canada and New Caledonia, helping to ease supply concentration.

In addition, there are 70 early-stage greenfield and brownfield projects under development across geographically diverse regions. Many are in the exploration, pre-feasibility or feasibility stages. Canada and Australia lead with 40 projects, representing close to 700 kt of potential nickel production. Beyond these, almost 650 kt of potential production is spread across projects in over 20 other countries.

The refining sector also has several operations in diversified regions under the base case, though there are markedly fewer opportunities in the high production case. In the base case, projects exist in Australia, Canada, New Caledonia, Finland and Japan, representing almost 10% of global refined nickel output in 2035. However, almost all of these operations (with the exception of Finland and New Caledonia) see declining production from today. In the high production case, only two new projects exist outside the incumbent players – one in Korea and the other in the Dominican Republic.

Composition of mined nickel supply growth to 2035 outside of today's top three producers



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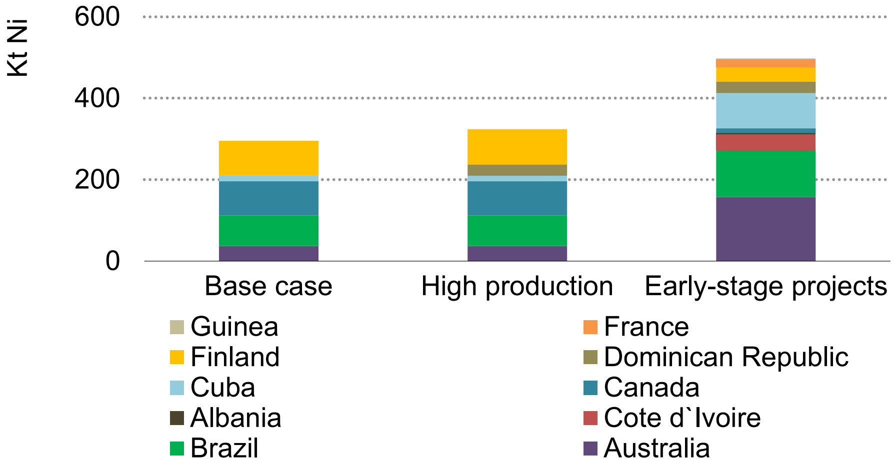
Considering projects at all stages of development, approximately 30 refinery projects exist globally in diversified regions worldwide, including in Australia, Brazil and Cuba. If these all came online, they could collectively add around 700 kt of capacity, with 20% of this located in Australia and 16% in Brazil. Many of these projects are in the exploration, scoping or pre-feasibility stage, indicating that they have a significant way to go before coming online. Challenges include higher initial and sustaining capital costs, along with increased operating expenses due to elevated energy and labour costs, all exacerbated by price volatility in the nickel market. These factors often make it difficult to secure the necessary capital to move operations forward, highlighting the need for additional support to develop more diversified supply chains (see Chapter 3).

Early-stage refined nickel supply from all projects outside today's top three producers, 2035



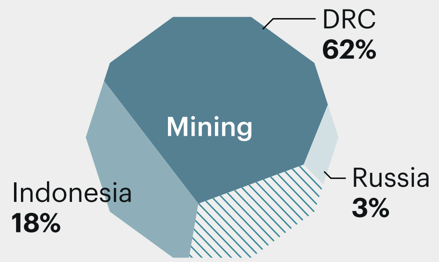
Source: IEA analysis based on Woodmac.

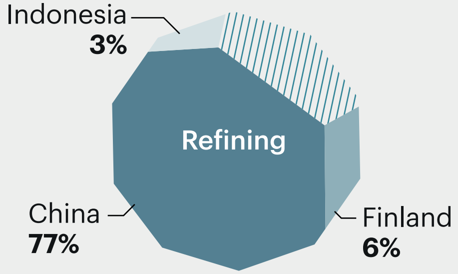
Outlook for cobalt

Cobalt

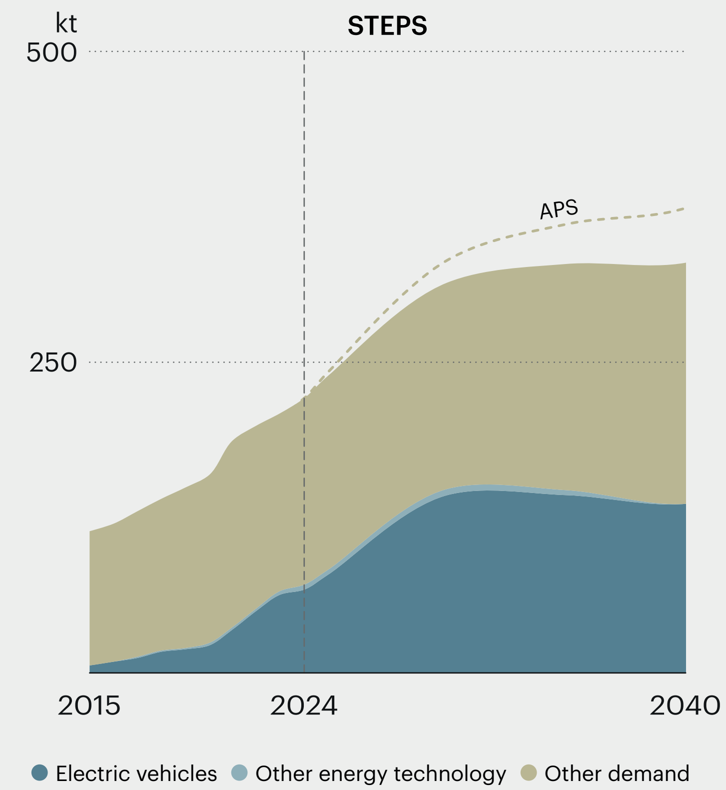
Co

Top three producers 2030

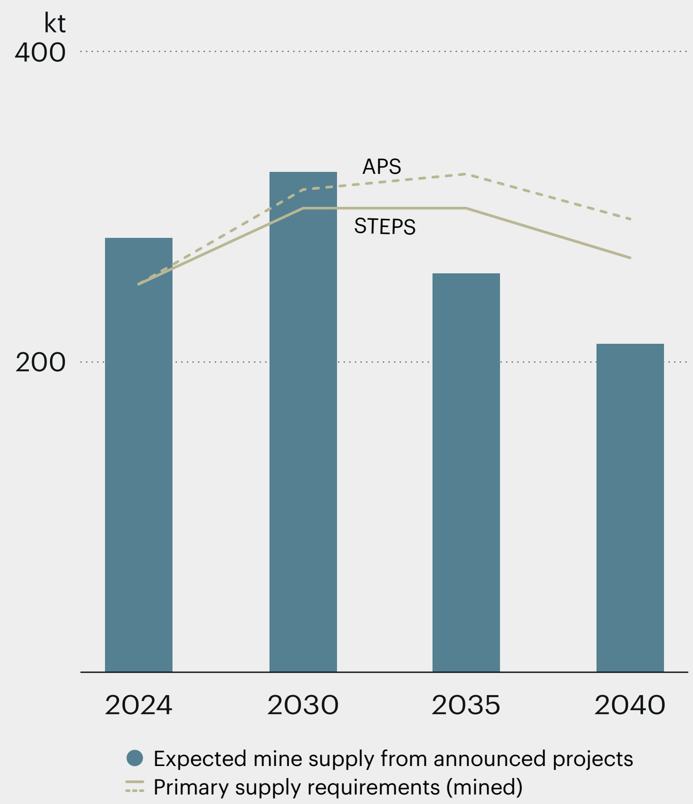




Demand outlook



Mining requirements



STEPS	2021	2024	2030	2040
Cleantech demand (kt)	**37**	**71**	**148**	**136**
Other uses (kt)	150	150	166	194
Total demand (kt)	**187**	**221**	**314**	**330**
Secondary supply and reuse (kt)	15	26	39	82
Primary supply requirements (kt)	**182**	**250**	**276**	**247**
Share of top three mining countries	76%	81%	83%	82%
Share of top three refining countries	82%	89%	87%	86%

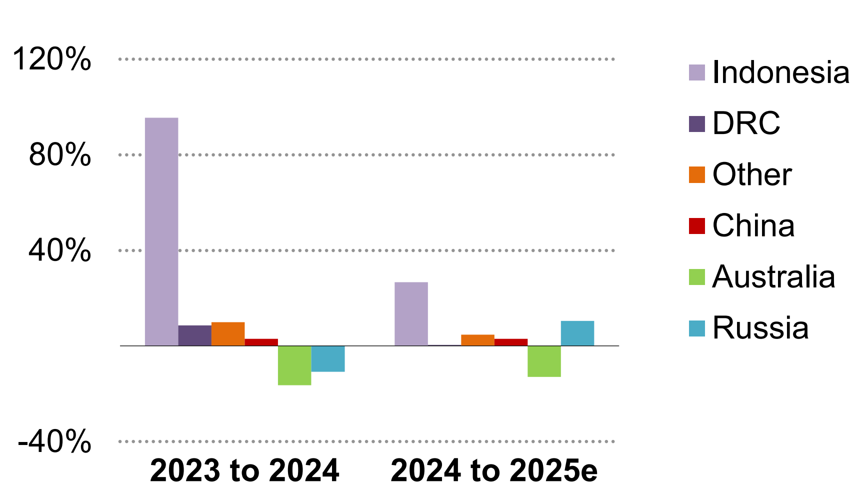
Recent market developments: Cobalt prices fell to a decade low due to an oversupplied market driven by increased output in the DRC and Indonesia; DRC imposed a temporary export ban

Cobalt prices continued to decline from their 2021 peak through early 2025, reaching their lowest levels in over a decade in February 2025. This was largely due to a combination of weakened demand prospects and persistent oversupply, primarily driven by the Democratic Republic of the Congo and Indonesia. Demand for cobalt grew by 10% over the last two years, but supply expanded even faster, with mined and refining output rising by about 25% each over the same period. The supply in the DRC was largely driven by increasing production of copper by Kisanfu, owned and operated by CMOC, which saw a 50% increase in production in 2024.

In response to low prices and to ease market pressure, the DRC imposed a four-month ban on cobalt ore exports, effective from 22 February 2025, triggering a price rally in the following four weeks. Whether the price increase will be sustained is yet to be seen, as China has accumulated substantial inventories of cobalt metal. If production growth continues despite the ban, it will merely shift future stockpiling from Chinese warehouses to ore concentrate in the DRC. Once the ban is lifted, prices are likely to fall again.

Another factor influencing price movements is Indonesia's rapidly increasing cobalt output. In 2024, Indonesia led absolute cobalt mine supply increases for the first time, rising by 95% compared with just under 10% growth in the DRC. Indonesia now supplies 12% of the global market, making it the second-largest supplier of cobalt. While the DRC government has stated its intent to work with the Indonesian government to ensure that the ban works to reduce oversupply, it is yet to be seen how this would materialise.

Change in mined cobalt supply by country



Notes: DRC = Democratic Republic of the Congo; 2025e = 2025 estimated values.

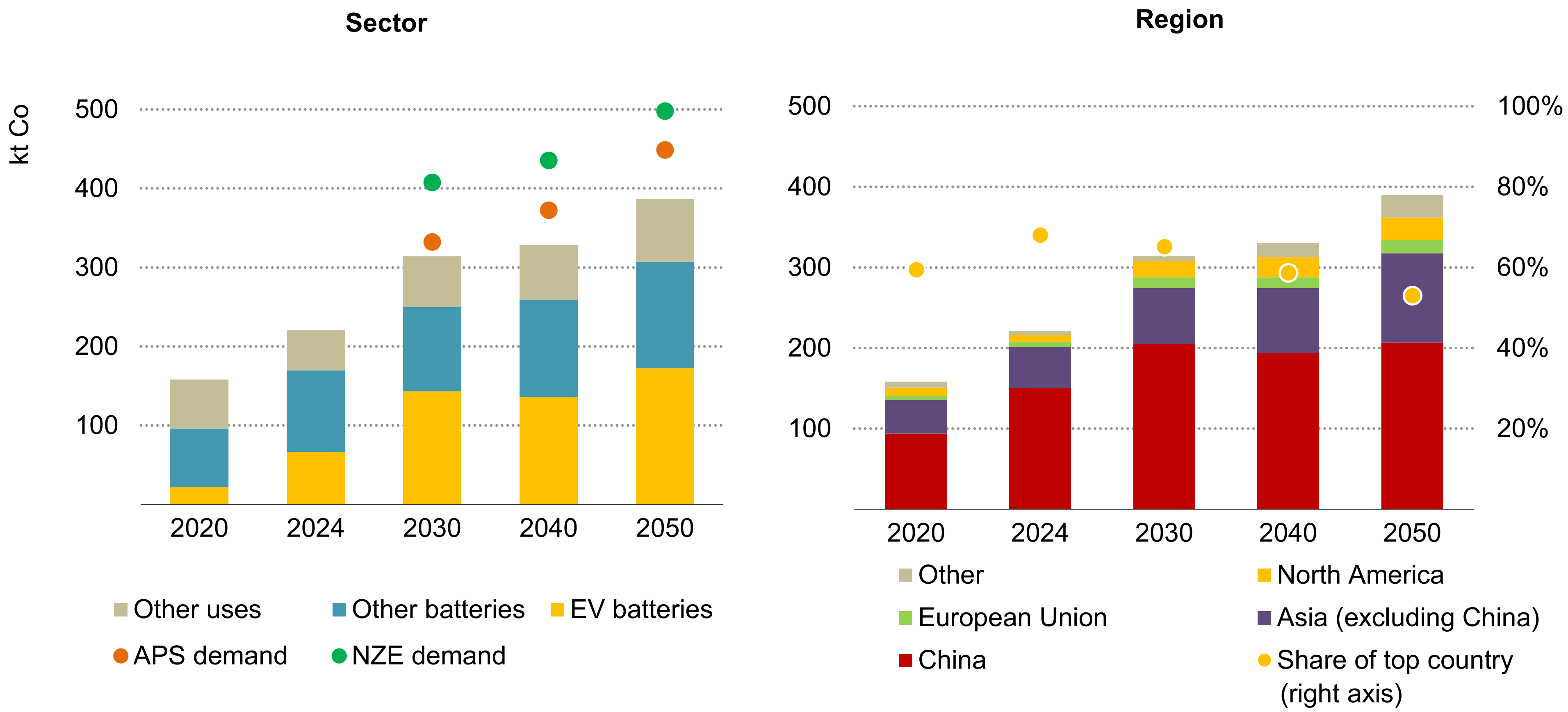
Much of Indonesia's rise in cobalt production has been due to cobalt's status as a by-product of nickel production. Several major players, including those in Obi Island, Weda Bay and the Morowali Industrial Park, saw 50% large increase in mined production in 2024. Over the past year, a Chinese-backed project owned by PT Halmahera Persada Lygend has started refinery production in Indonesia, making 2024 the first year for Indonesia-produced refined cobalt.

In the same week as the DRC's export ban, the government introduced new regulations granting the state-owned Enterprise Generale du Cobalt (EGC) exclusive rights to purchase and export artisanal cobalt. Amid persistently low prices, artisanal cobalt mining dropped by 13% between 2020 and 2024, now accounting for less than 2% of the country's total output.

Another notable development in the cobalt market involves international agreements between the DRC and other countries. The largest DRC mines are currently backed by Chinese players, like CMOC, and creditors who have provided over USD 11 billion in loans and grants to the some of the largest producers in the region, including Tenke Fungurume, Kinsenda and Sicomines. However, the DRC is now exploring partnerships beyond China. In January, the government announced ongoing discussions with investors from Saudi Arabia, the European Union and India, seeking to diversify its funding sources. The United States has also been in talks with the DRC on a potential US-DRC minerals partnership agreement aimed at increasing US private sector investment in the development of the country's mineral resources.

Demand: China continues to dominate cobalt demand as EV battery demand surpasses consumer electronics by the late 2020s

Global cobalt demand outlook by sector and region



Demand: Projected cobalt demand for EV batteries has been revised down, but it remains the largest source of demand growth

Historically, cobalt was primarily used in portable batteries for electronics, accounting for over 40% of cobalt's total demand in 2015. It is also employed in alloys due to its strong resistance to corrosion and wear, making it well suited for applications such as jet engine turbines, nuclear power plants and chemical-processing industries. In recent years, demand has increasingly shifted towards battery technologies, driven by cobalt's role in nickel-rich chemistries. In 2024, energy technologies accounted for 30% of total cobalt demand, a share projected to rise to just over 40% by 2040 in the STEPS, to 50% in the APS and over 55% in the NZE Scenario.

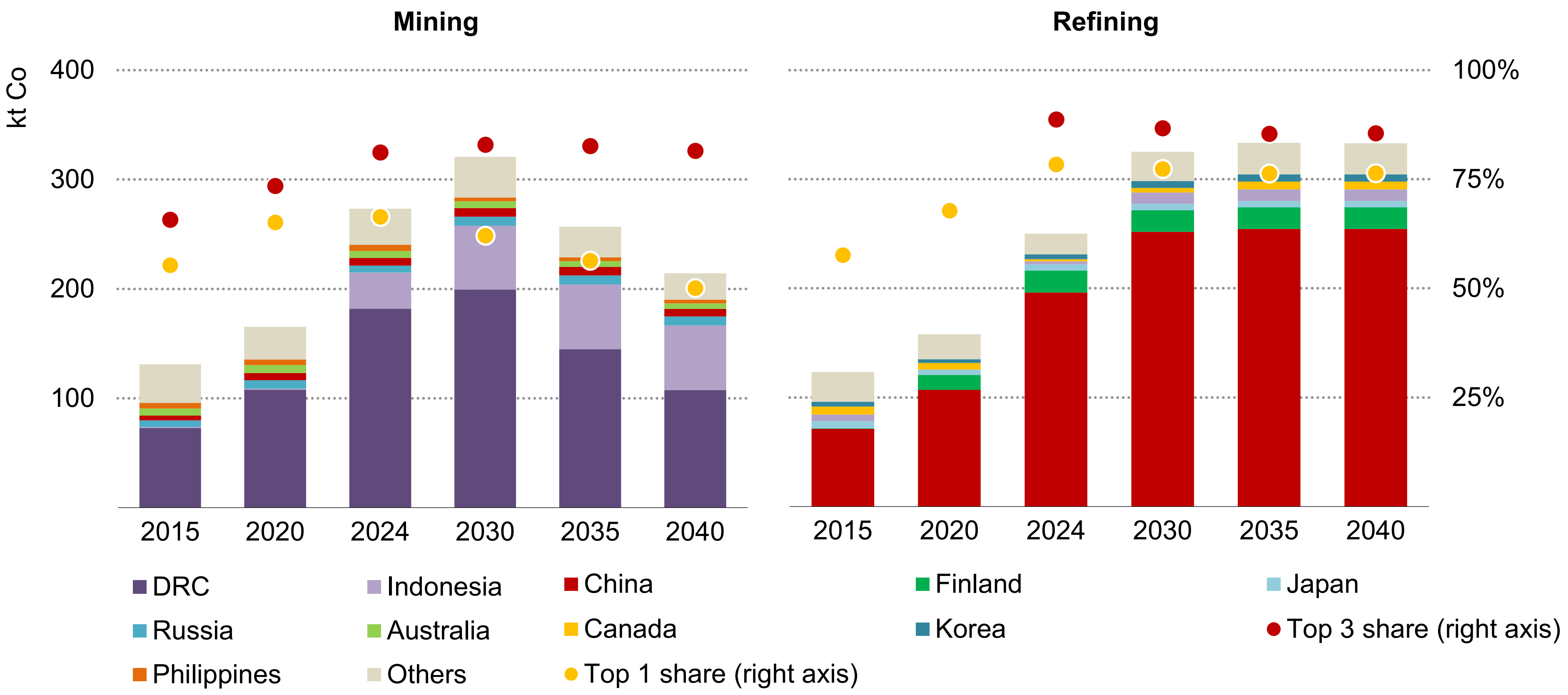
Global cobalt demand rose by 6% from 2023 to 2024 to 220 kt. Unlike from 2022 to 2023, when the largest demand growth was driven by use in EV batteries, the largest growth in 2024 occurred in other sectors. This was due mainly to lower EV sales in some markets and the changing composition of battery chemistries towards less cobalt-rich ones.

Nevertheless, in the outlook period across all scenarios, the largest growth in cobalt demand continues to come from EV batteries, more than doubling in the STEPS and rising more than fourfold in the NZE Scenario. In the STEPS, total cobalt demand reaches almost 400 kt by 2050, while accelerated EV sales and faster renewables deployment push demand to around 500 kt in the APS and the NZE Scenario. However, cobalt demand for EV batteries has been revised down by 25% for 2040 compared with last year's Outlook due to shifts in battery chemistry choices. Meanwhile, demand for cobalt in superalloys grows steadily, driven by the aerospace and defence sectors.

China remains the largest consumer, accounting for 70% of total cobalt demand in 2024, mainly for portable electronics. Japan and Korea follow, together making up over 15%. Looking ahead, China's cobalt demand for EV batteries overtakes that for electronics by the mid-2020s. The European Union, North America and Africa also see strong growth in cobalt demand for battery precursors, rising from 1 kt to 15 kt by 2040.

Supply: Rising mined cobalt production in Indonesia diminishes the DRC's dominant market position, bringing its market share down to 50% by 2040

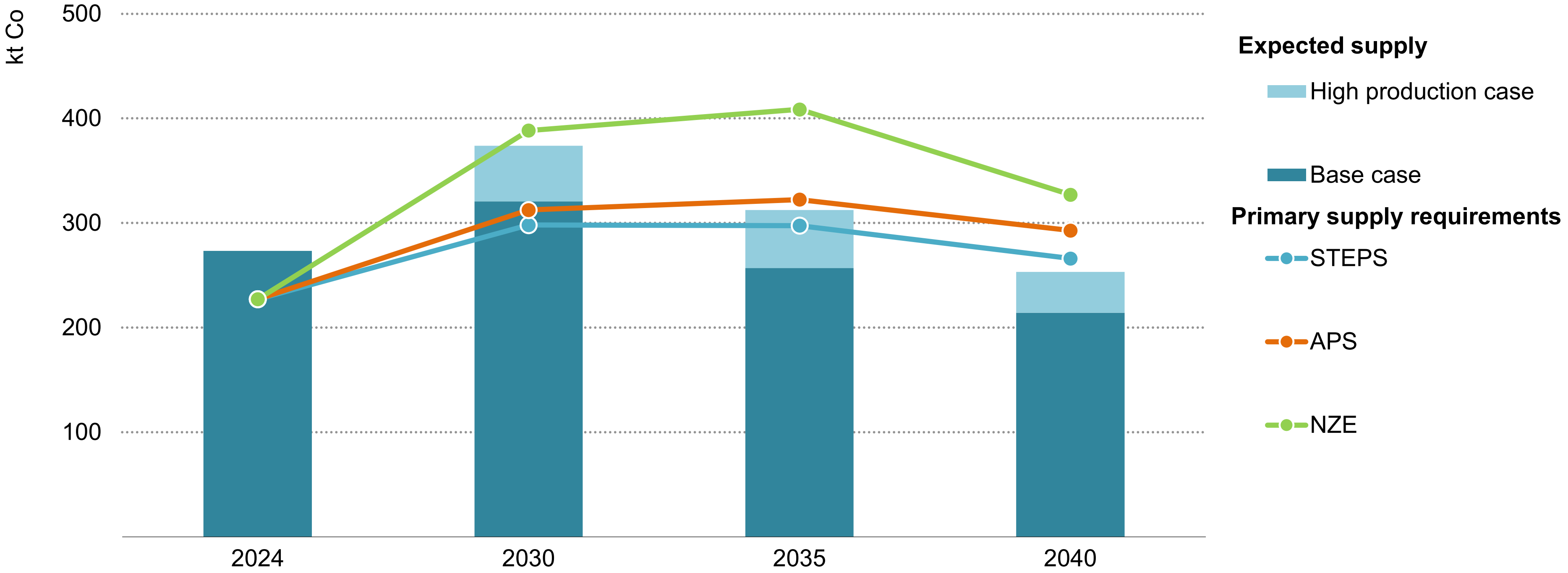
Cobalt production from operating and announced projects in the base case



Note: DRC = Democratic Republic of the Congo.

Supply: A near-term supply surplus persists, but declining mining production points to a different picture post-2030

Expected mined cobalt supply from operating 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 Overview section for definitions of the base and high production cases.

Supply: Oversupply is set to persist in the near-term, but mined output starts to decline post-2030 despite Indonesia's growing production

Mining

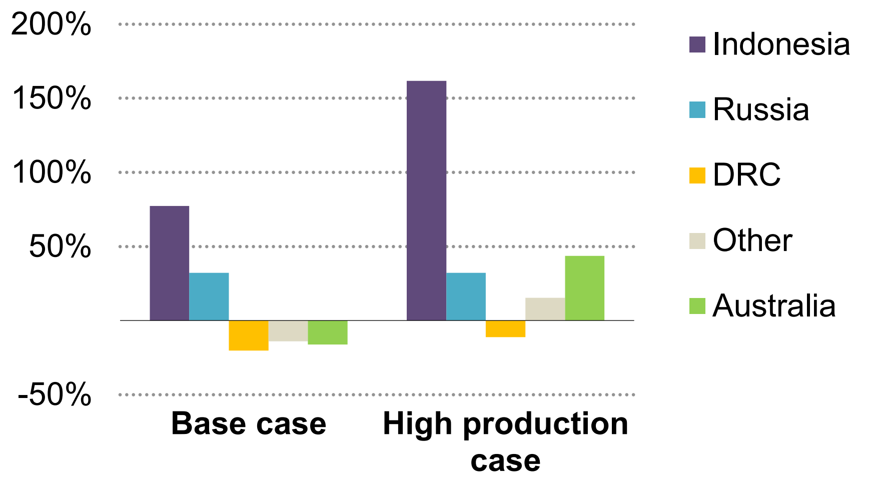
Mined cobalt supply surplus is expected to persist in the near term as production keeps growing faster than demand in the STEPS. From around 2030, production in the DRC starts to decline, driven by diminishing ore quality, which is only minimally offset by Indonesia's production expansions in the base case. As a result, total mined supply shrinks by a third during the 2030s before levelling off at around 215l kt, with DRC production alone falling by 45% over this period.

Indonesia already accounts for over 10% of total mined cobalt supply and is projected to expand output by almost 80% to 2040 in the base case, overtaking the DRC by the 2040s. In the high production case, Indonesian overtakes the DRC several years earlier. As Indonesian nickel production drives this uptick, by 2040 almost 35% of global cobalt is produced as a by-product of nickel.

Refining

China remains the leading cobalt refiner, accounting for 78% of the market in 2024, a trend that continues throughout the projection period. However, a closer look at cobalt sulphate, a key precursor for EV batteries, reveals a shifting landscape. The cobalt sulphate market grows by 45% by 2035. In 2024, Indonesia began producing cobalt sulphate, capturing 3% of the global market. By 2030, its production triples, increasing its market share to 7%. Europe and North America nearly double cobalt sulphate output in the base case, while Korea boosts its output to 6 kt by 2030, a 1.5-fold increase.

Changes in mined cobalt production, 2024 to 2035



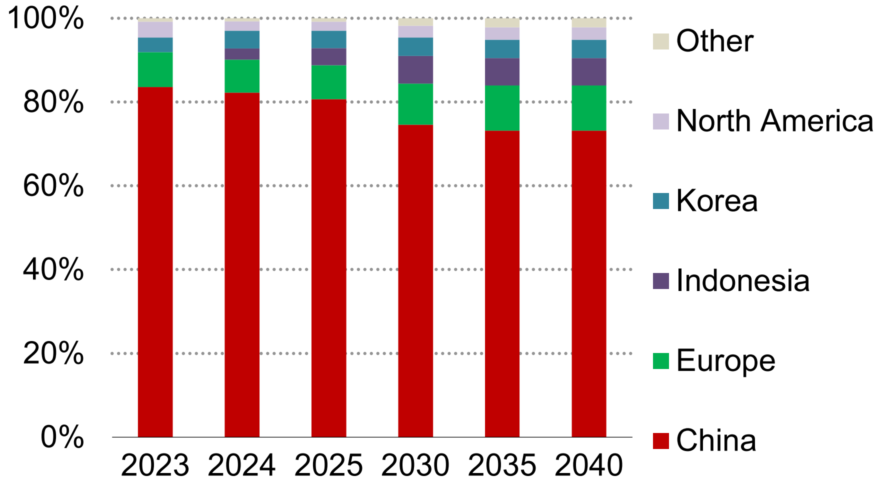
Note: DRC = Democratic Republic of the Congo.

The share of secondary cobalt supply in total demand (excluding direct-use scrap) was about 12% in 2024, increasing by 16% year-over-year. A combination of policy actions that incentivise higher recycling of both consumer and EV batteries mean that this share grows further to 25% by 2040 in the STEPS.

Market balances

The cobalt market surplus is expected to persist in the near term. However, as mined output starts to decline post-2030, the surplus begins to disappear, eventually reaching a 50 kt deficit by 2040 in the base case and 14 kt in the high production case relative to primary supply requirements in the STEPS.

Geographical concentration of cobalt sulphate refining in the base case



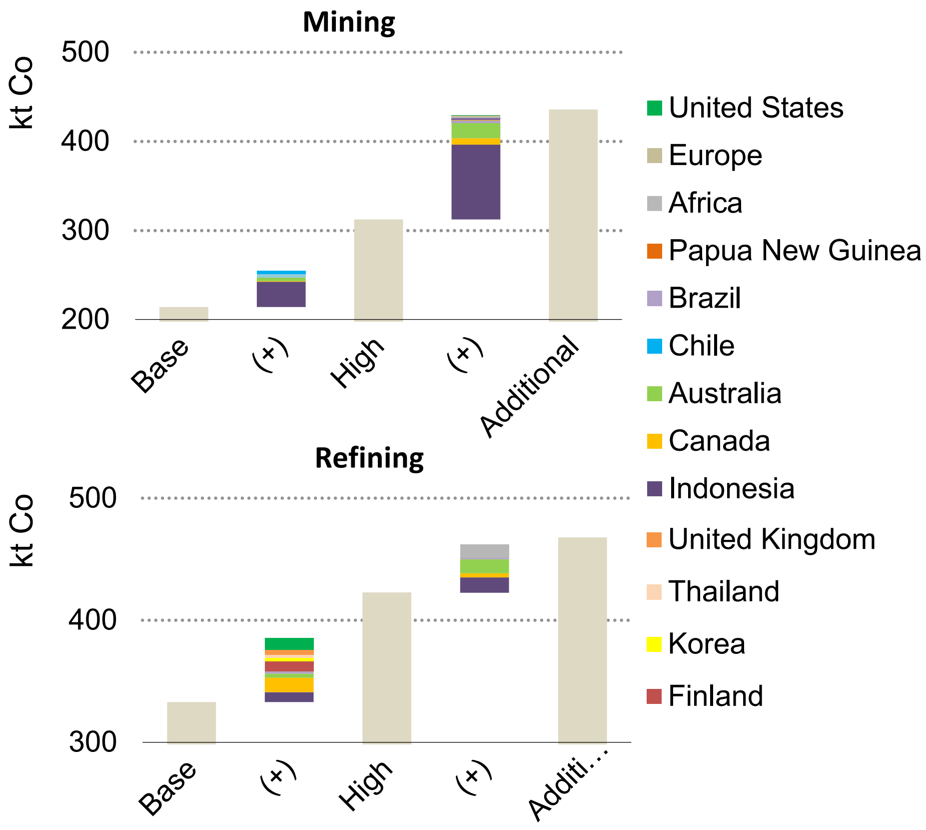
IEA. CC BY 4.0.

Prospects for diversified supplies: A wide range of countries and regions provide potential for cobalt supply diversification

Despite high levels of concentration in mined and refined cobalt supplies, there are some opportunities for diversification. In the high production case, 40 kt of additional diversified mined supply could emerge by 2035, distributed among producers such as Australia, Canada, Zambia and Chile. There are also numerous cobalt projects in the early-stage pipeline which, if brought online, could add an additional 123 kt of supply by 2035. Almost 70% of this production is located in Indonesia, while the remaining 33 kt are spread across other countries and regions, including Australia, Canada, Africa, Brazil, the Philippines and Europe.

Refined cobalt production offers a broader range of diversification prospects. In the high production case, 10 countries add over 100 kt of refined supply. Among these, Canada, the United States and Finland add about 20 kt of additional supply each, with further production materialising in Australia, Brazil, Korea, the United Kingdom and Thailand. Beyond projects considered in our scenarios, additional announced early-stage projects could introduce 40 kt of supply across diversified regions, including 11 kt in Africa outside the DRC.

Potential diversification of mined and refined cobalt supply, 2035



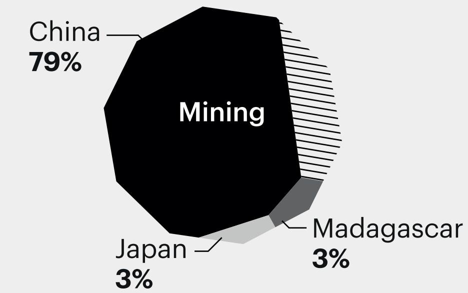
Outlook for graphite

Graphite

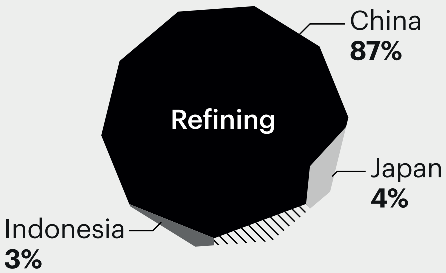
C

Top three producers 2030

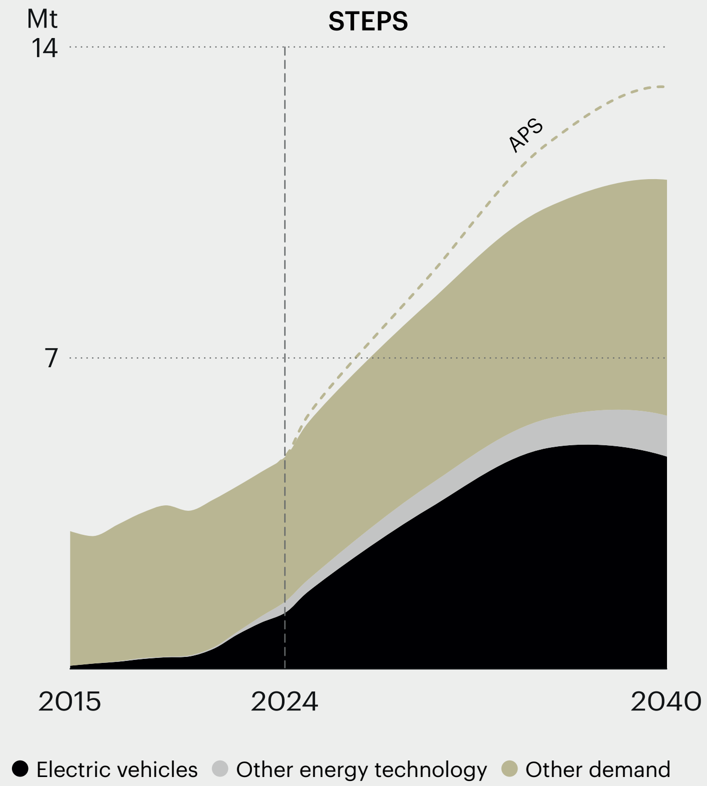
Total supply (all grades)



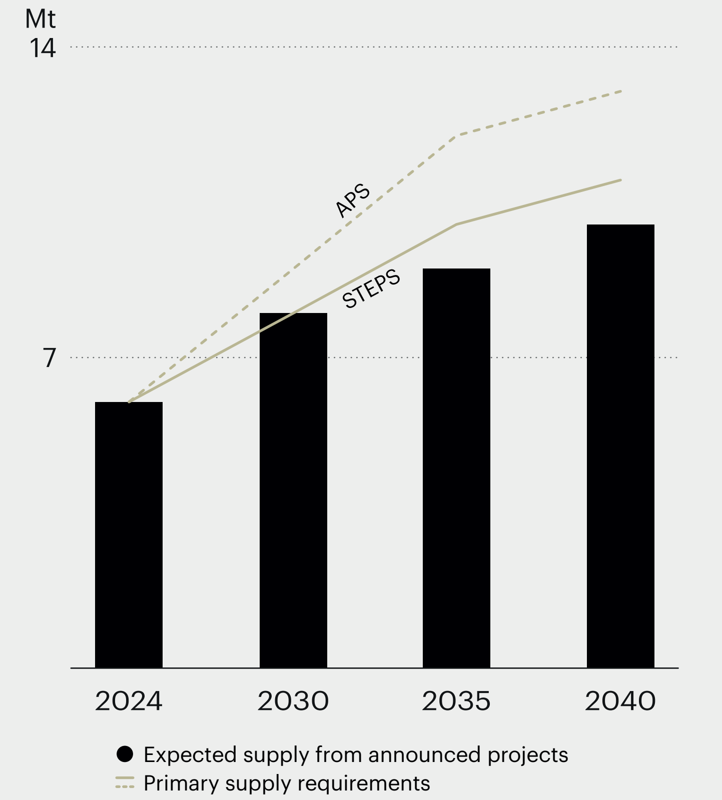
Battery grade supply



Demand outlook



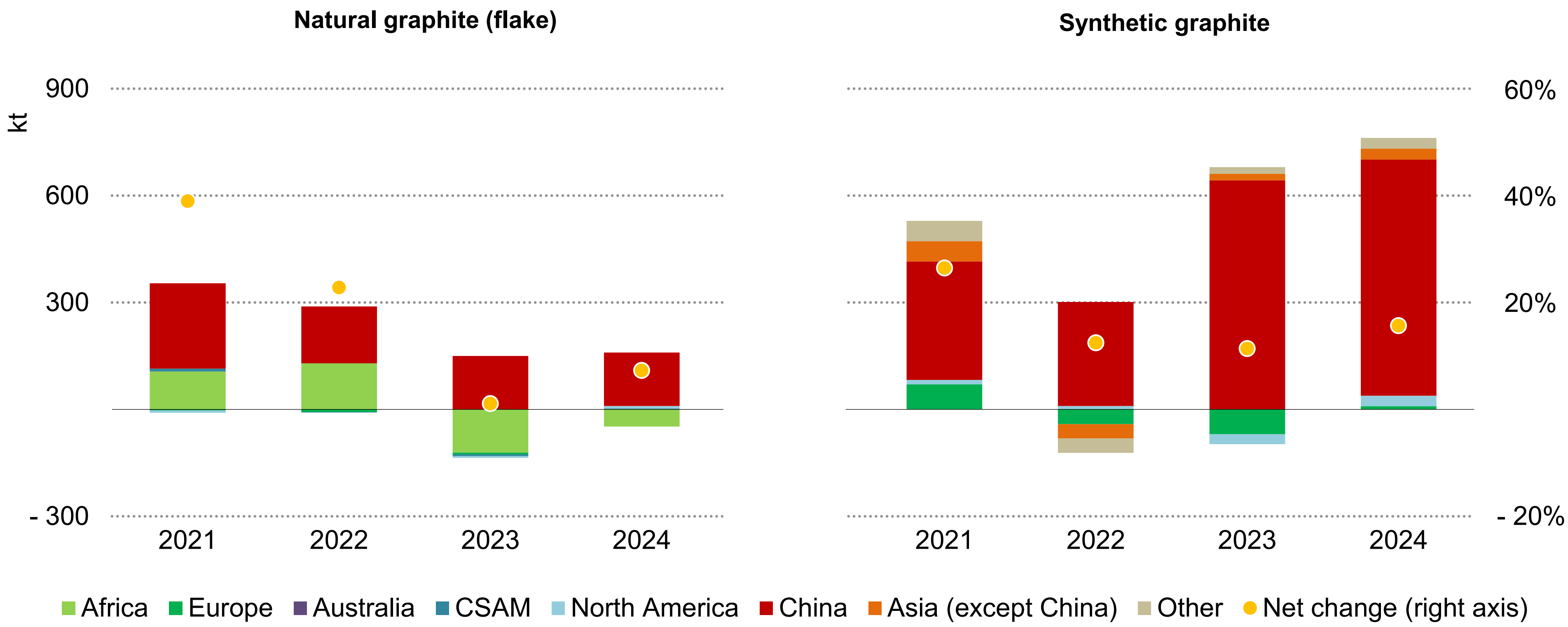
Supply requirements



STEPS	**2021**	**2024**	**2030**	**2040**
Cleantech demand (kt)	**487**	**1 505**	**4 114**	**5 700**
Other uses (kt)	3 326	3 260	4 105	5 309
Total demand (kt)	**3 813**	**4 766**	**8 219**	**11 010**
Secondary supply and reuse (kt)	108	127	162	227
Primary supply requirements (kt)	**4 269**	**6 157**	**8 057**	**10 762**
Share of top three mining countries	90%	93%	86%	86%
Share of top three refining countries	100%	99%	93%	92%

Recent market developments: Synthetic graphite continues to gain shares over natural graphite

Annual change in natural graphite and synthetic graphite production



Note: CSAM = Central and South America.

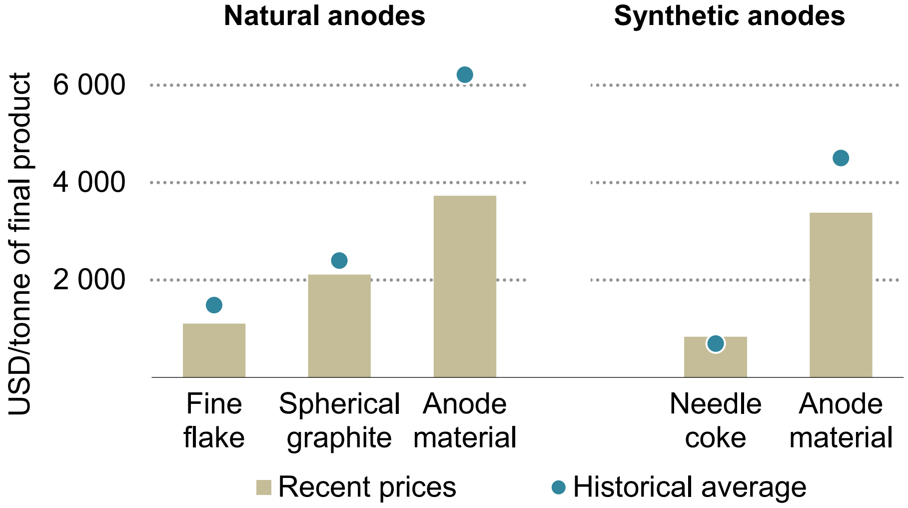
Recent market developments: Projects accelerate in diversified areas, but synthetic supply faces headwinds in China due to petroleum coke supplies

Global graphite consumption grew by 8% in 2024, reaching 4.8 Mt, with most of the growth driven by batteries. Battery anode manufacturers increasingly favour synthetic graphite, up 30% from the previous year. In contrast, demand for natural anode materials remains stable at around 280 kt of refined materials, equivalent to about 700 kt of flake graphite.

Synthetic anode supply is rapidly expanding to meet rising graphite demand, pushing anode prices well below historical averages. Medium-power grades are currently quoted at around USD 3 400 per tonne, marking a 25% year-on-year decline from 2023. Total synthetic graphite production grew to over 4.3 Mt, requiring about 5.2 Mt of petroleum coke, the key feedstock for graphite synthesis. However, recent spikes in material input costs and falling anode prices are significantly squeezing margins for synthetic anode producers. At the start of 2025, China's needle coke market saw substantial price increases, reaching USD 750 per tonne. This surge was driven by local refineries‘ exposure to sanctioned crude suppliers, port measures to restrict access to sanctioned ships and newly implemented tax policies.

Mined natural graphite grew more slowly in 2024. China’s graphite sector, which accounted for about 80% of global natural flake supply, saw a 7% increase this year. However, African production dropped to 120 kt, a 30% decline, due to operational challenges. Mozambique’s Balama mine declared force majeure due to civil unrest, and Tanzania’s Lindi mine faced issues after its owner went into administration, compounded by logistical problems at the Dar es Salaam port. As a result, refined (spherical) natural graphite production slightly declined to 310 kt in 2024.

Battery-grade graphite supply chain prices, Q1 2025



Note: Anode material prices are for medium-power grades (320-340 milliampere-hours per gramme).
Sources: IEA analysis from Woodmac, Fastmarkets and S&P Global.

Supply diversification amid growing trade restrictions

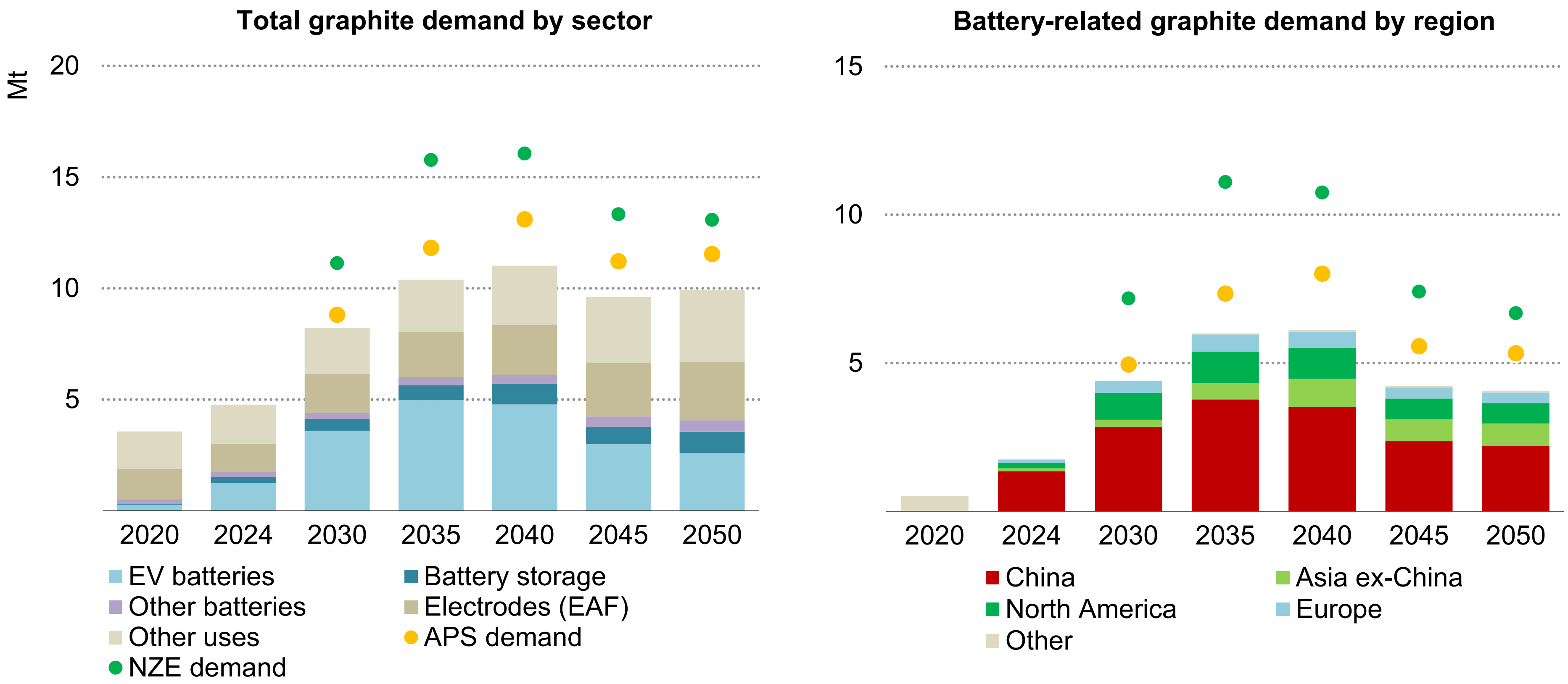
The lack of alternatives for battery anodes, the absence of secondary sources and the high level of supply concentration make graphite supply chains increasingly vulnerable to disruptions and shocks among battery materials. Fiscal and regulatory measures adopted from late 2023, including export controls, are creating strong incentives to accelerate investments in diversified supplies, as market players anticipate possible trade fragmentation.

China implemented export controls on graphite-related items in December 2023, requiring exporters to obtain a licence to ship these items abroad. In December 2024, China announced tightened controls for exports to the United States. While export volumes keep flowing, some consumers are wary of risks related to vulnerabilities related to the short duration of permits, which need to be renewed every six months. From the consumer side, policies are being introduced to disincentivise sourcing graphite from China, including a 25% tariff in the United States starting in 2026 and potential similar tariffs in Canada. Market players have also reported that US Foreign Entity of Concern regulations have increased interest of downstream industrial consumers for alternative supplies.

New supply sources are emerging to address these challenges. In Central and South America, the South Star and Graphcoa mines began production in in October and December 2024, respectively. In Europe, investor interest is rising, highlighted by Norge Mining's acquisition of the Skaland mine in northern Norway in December 2024. In October 2024, Norwegian company Vianode opened its Herøya plant, aiming to produce 200 kt of anode materials by 2030. In Indonesia, the BTR Morowali project launched with 80 kt capacity, with plans to double capacities to 160 kt. Balama could also supply the ramping-up Vidalia refinery in Louisiana. Meanwhile, Ukraine's supplies, particularly Volt Resources' Zavalievsky project, which began producing small volumes in late 2024, are attracting growing attention.

Demand: EVs are driving the future of the graphite market, although the increasing use of silicon is expected to play a larger role in the longer term

Global graphite demand by sector and region in the STEPS



Note: EAF = electric arc furnace.

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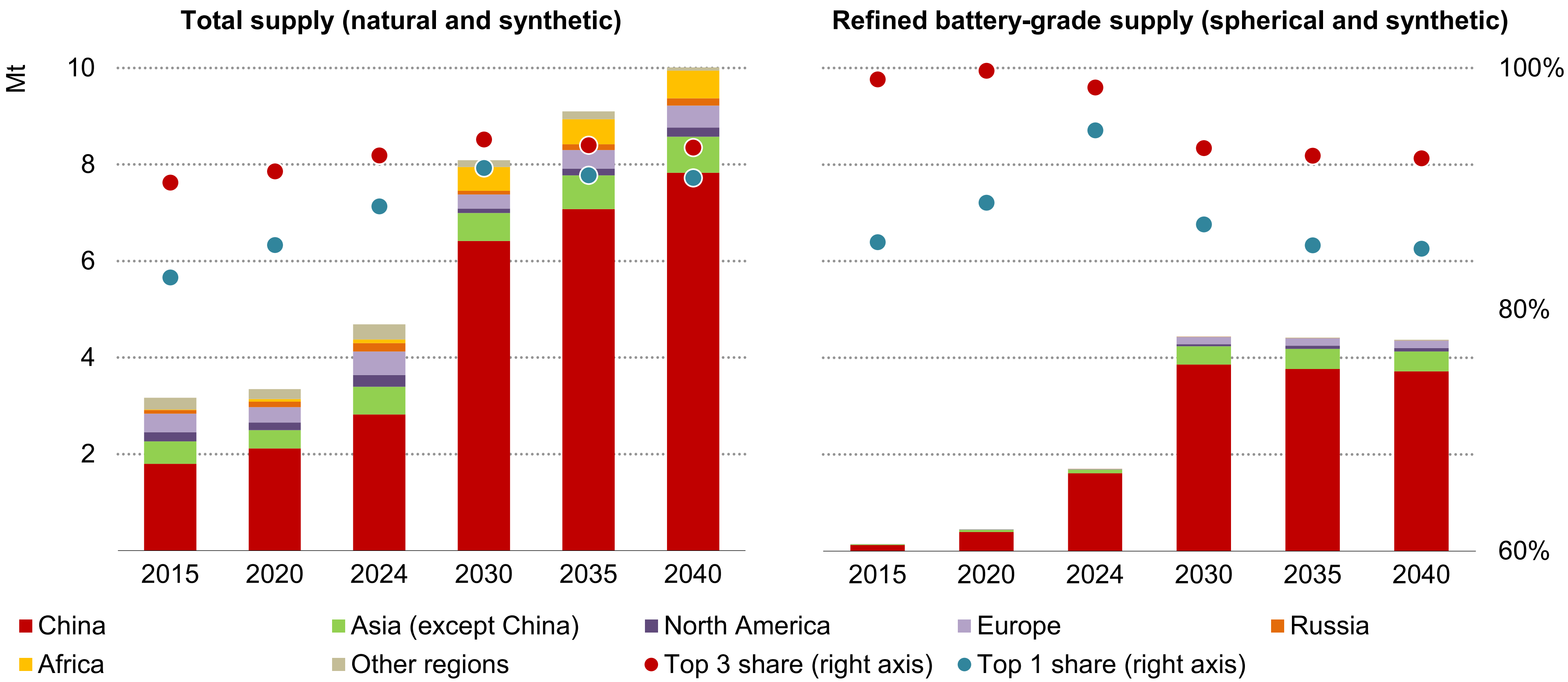
Supply: Despite progress in new projects in diversified regions, supply concentration remains durably high, particularly for battery-grade graphite

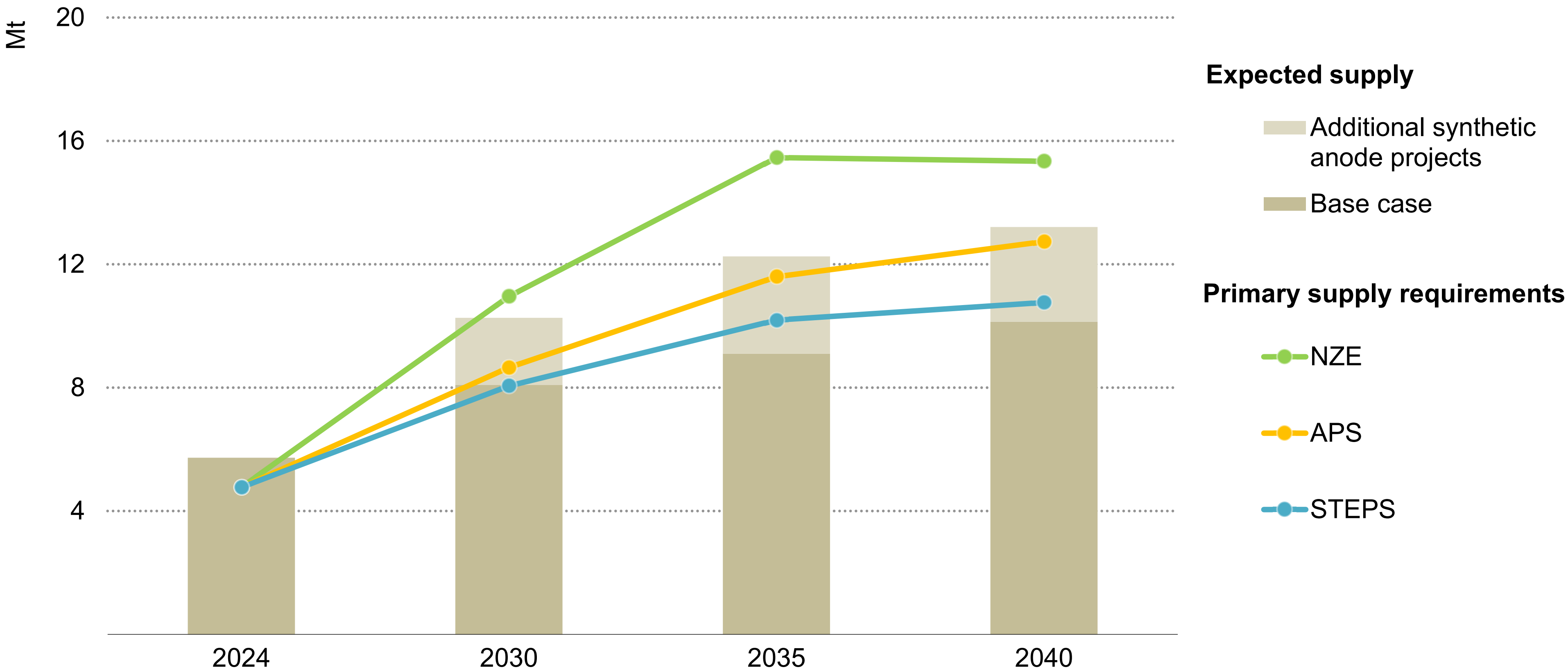
Total and battery-grade graphite supply from existing and announced projects in the base case



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: Large synthetic graphite capacities leave the door open to balance the market

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 Overview section for definitions of the base and high production cases.

Outlook: Graphite is one of the materials that are most exposed to potential supply risks, requiring urgent efforts for diversification

Demand

In the STEPS, total graphite demand is set to reach over 10 Mt by 2035, doubling from today. Graphite is the most prominent critical mineral by weight in a typical EV or energy storage battery: an average electric car contains about 60 kg of graphite anode materials. As with cathode minerals such as lithium, the rapid growth of EV battery production has reshaped the graphite market, and the continued expansion of large-scale manufacturing provides further momentum for demand growth. Demand from lithium-ion batteries triples from 1.8 Mt to over 6 Mt by 2035 in the STEPS.

In the medium term, graphite remains the most common anode material for all lithium-ion battery chemistries. Starting from 2030, rising silicon content in battery anodes is set to reduce the share of graphite gradually from the EV sector. Adding silicon to the anode boosts the battery's energy density. While 1 kWh of storage typically requires 900 grammes (g) of graphite, incorporating 100 g of silicon can reduce the graphite requirement by up to 500 g. Annual graphite demand from EV batteries thus peaks at 5 Mt around 2035 before falling by over 2 Mt in the period to 2050. While this shift promises enhanced battery performance, it may not simplify the sourcing of anode materials. High-purity silicon can improve battery efficiency, but, like graphite, it faces similar, if not more significant, supply challenges, particularly due to a highly concentrated supply base (see the Silicon section).

The growing role of synthetic graphite over natural graphite also has a moderating effect on aggregate demand. Due to the substantial losses that exist when transforming natural graphite into battery-grade graphite, a growing reliance on synthetic graphite reduces overall graphite demand from the battery sector in volume terms.

Supply

Synthetic graphite supply for battery anodes could reach 4 000 kt by 2030, up from 1 550 kt today. With ample production capacity, the industry is well-positioned to scale output. The share of synthetic graphite in batteries is expected to increase in the coming years. In 2024, China continued to control nearly all synthetic graphite production. Efforts to diversify supply sources could increase the share of diversified players to almost 15% by 2030 based on the current project pipeline. Production of synthetic graphite may increase in Japan, Europe and North America. In December 2024, the US Department of Energy announced support for a project in Tennessee with an annual capacity of 31.5 kt.

Efforts to diversify mined natural graphite supply are taking shape. While output from Chinese mines is expected to stabilise and possibly decline slightly, significant projects are emerging in Africa. A steady stream of new projects is under exploration and development, including in Malawi, where a mining junior backed by Rio Tinto is developing a titanium ore (rutile) deposit.

North America may also provide potential supplies, with four projects under development in Canada, in addition to the already operating Lac des Îles mine. This includes the Nouveau Monde Graphite project, which received CAD 50 million (Canadian dollars) from the Canadian Growth Fund and the Government of Quebec. Several projects are also under development in Australia, notably Quantum's Uley and Renascor's Siviour projects (100 kt each). Some projects in Europe have reached advanced permitting stages and are currently identified as strategic under the Critical Raw Materials Act, such as the Nunsvaara South mine in Sweden (120 kt). However, these projects may face higher cash costs compared with existing Chinese counterparts, due to factors such as logistics, higher strip ratios and lower grades.

The process of refining natural graphite into battery anode materials involves steps such as spherodisation, coating and purification. Spherodisation is the supply chain step with the highest level of geographic concentration, dominated by China, thus creating risks both for downstream consumers and upstream mine projects. Some diversified natural graphite refining projects may emerge, including Urbix's Alabama graphite plant, supported by the US Department of Energy. Australia is utilising its Critical Minerals Fund to finance two battery-grade graphite projects, supporting the domestic refining of its raw material supplies. This includes loans to the Siviour project and the smaller EcoGraf project.

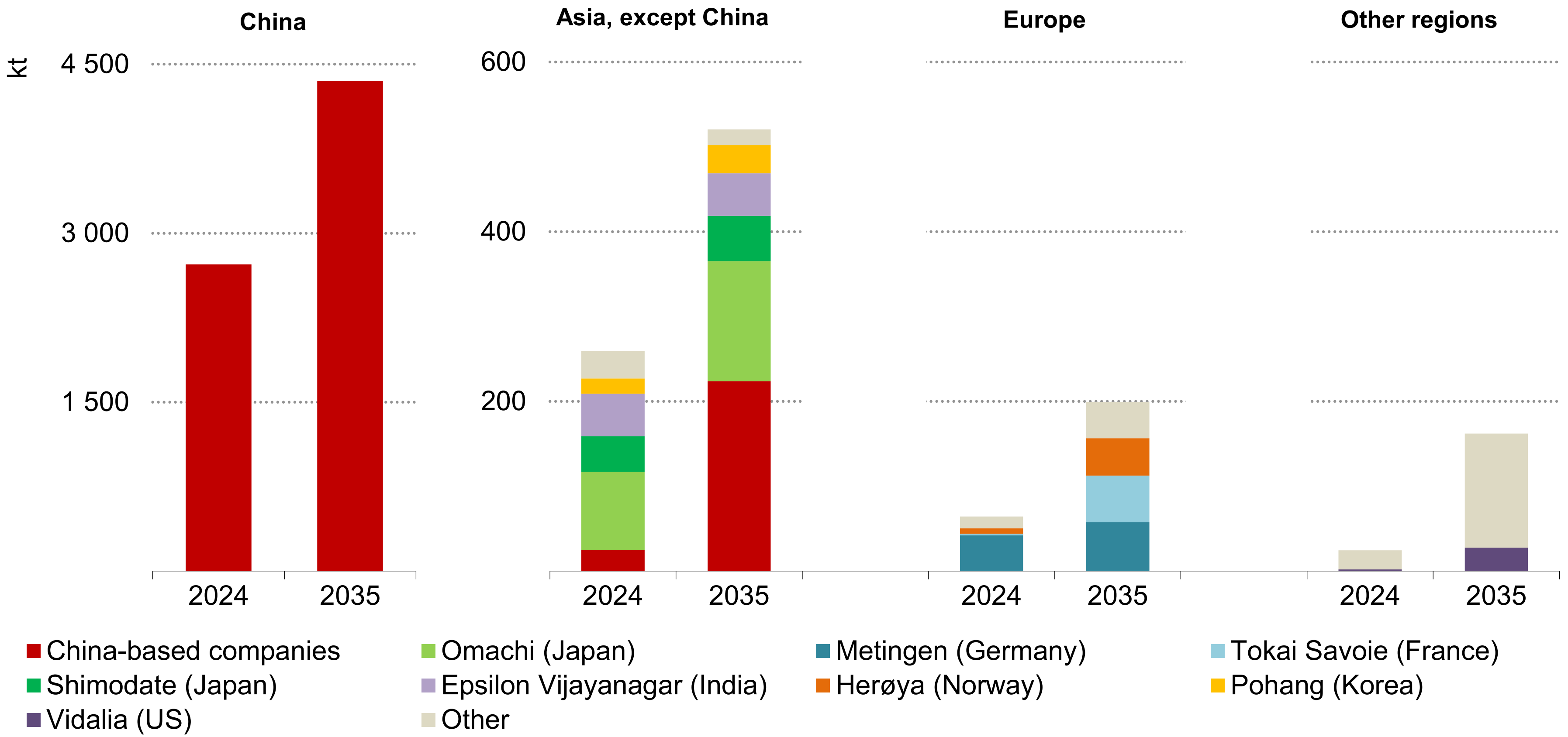
Compared with other battery metals such as cobalt, graphite recycling is generally considered economically challenging. However, some hydrometallurgical recyclers, such as Atilium in the United Kingdom (UK), are aiming to supply 16 kt of recycled materials to the battery anode market between 2026 and 2029.

Prospects for refining diversification

A number of key projects are poised to unlock prospects for supply diversification, potentially tripling the amount of graphite available outside the dominant producer. Japanese companies, with strong technical know-how, may play a key role with investments in domestic projects, notably possible expansions of Resonac's Omachi and Shimodate plants, but also investments in Europe, including Tokai Cobex's investment in the Carbone Savoie plant in France as well as in the United States. Other key projects are either under development or expanding in Europe (Heroya in Norway and Meitingen in Germany) and Asia (Epsilon in India and Pohang in Korea).

Prospects for diversified supply: Currently very limited, supply options outside the dominant supplier could triple if a few planned, large-scale projects successfully come online

Battery-grade graphite material supply capacities in the base case



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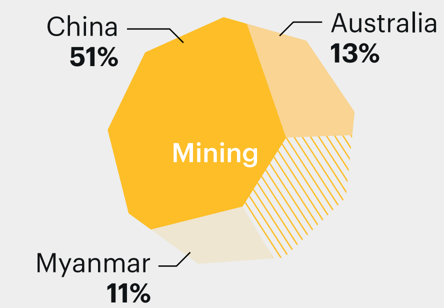
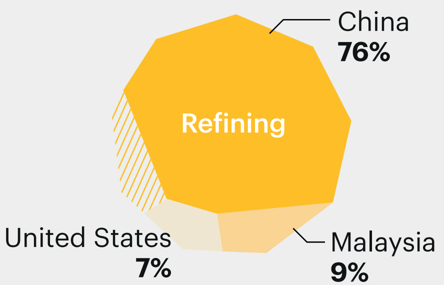
Outlook for rare earth elements

Rare earth elements

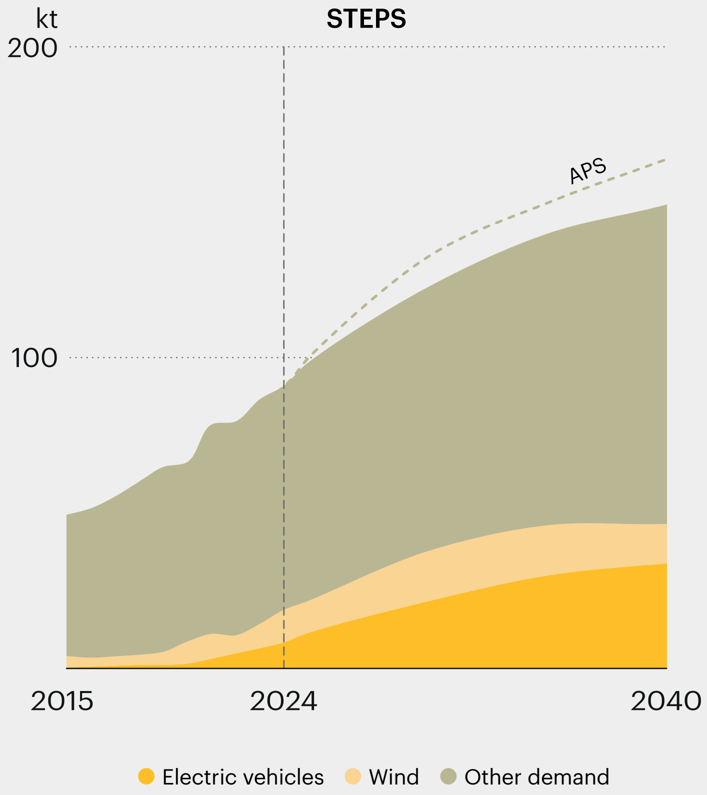
Nd Pr Dy Tb

Top three producers 2030

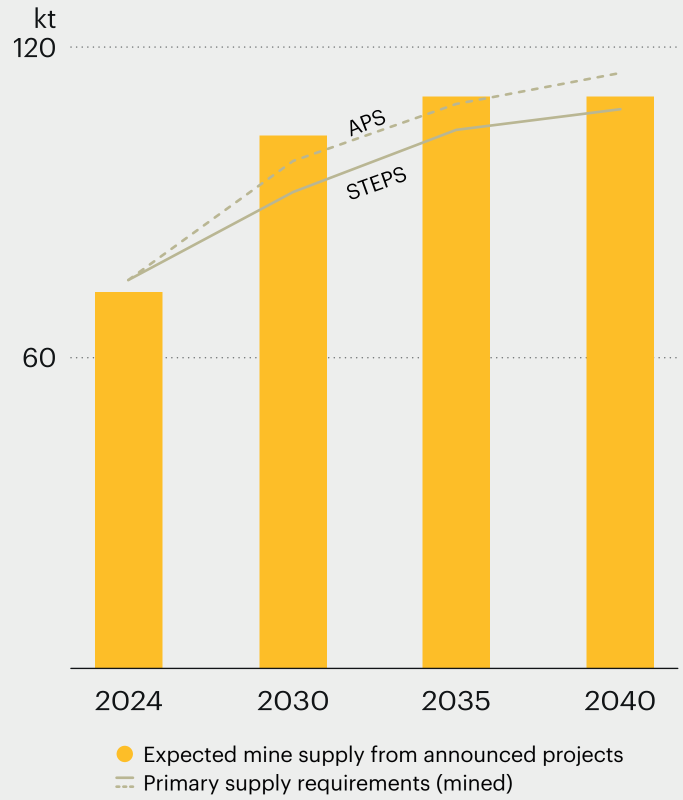




Demand outlook



Mining requirements



STEPS	2021	2024	2030	2040
Cleantech demand (kt)	**11**	**19**	**38**	**47**
Other uses (kt)	67	72	85	103
Total demand (kt)	**78**	**91**	**123**	**150**
Secondary supply and reuse (kt)	22	27	32	43
Primary supply requirements (kt)	**55**	**69**	**91**	**107**
Share of top three mining countries	81%	86%	74%	76%
Share of top three refining countries	98%	97%	92%	92%

Recent market developments: Looming threats to today's well-supplied markets

The outlook for the supply of magnet rare earth elements (REEs) (neodymium [Nd], praseodymium [Pr], dysprosium [Dy] and terbium [Tb]) that seemed sufficient to meet demand requirements in early 2024 has since been threatened by several risks that emerged during 2024 and early 2025. Growing geopolitical tensions between regions and domestic governance issues in one of the largest suppliers can disrupt the demand and supply balances for these minerals that are essential for manufacturing high-performance permanent magnets (often neodymium iron boron [NdFeB]) used to build powerful motors for several cutting-edge applications, including EVs and wind turbines.

Supplies from Myanmar at risk

Myanmar has remained a largely overlooked supplier of several critical minerals such as rare earth elements, antimony and tin. For decades, the country has been exporting raw materials from its Kachin State region across the border to its neighbour China for processing and refining. In 2024, its share of mined supply for heavy rare earth elements such as dysprosium and terbium was around 45% of global supply; however, it has remained a largely informal and underreported sector.

In November 2024, the Kachin Independence Army announced that it had taken control of the country's rare earth mining region, causing local mining to halt and borders to close. Since then, the export of rare earth raw materials to China has significantly decreased. While the border remains strictly controlled, as of March 2025, a gradual flow of existing inventories to China has restarted. During the period of complete border closure, China had sufficient inventories of raw materials at refining plants, from domestic mines and from imports from the Lao People's Democratic Republic (Lao PDR) and Brazil. Nevertheless, if the border conflicts continue, there is likely to be some supply-side shortages for heavy rare earth (HREE) feedstocks, mostly ionic adsorption clay-based, at Chinese processors. The situation in Myanmar has also greatly affected the supply stability of chemicals, electricity and water for mining operations, making it difficult to resume supply in the very near term.

On the demand side, the appetite for magnet rare earths used in EVs, wind turbines, industrial motors and robotics is expected to increase albeit at slightly slower rates in some sectors. Therefore, if the conflict in Myanmar continues, it could lead to a price increase for the medium and heavy rare earths, while the impact on light rare earths would be relatively limited

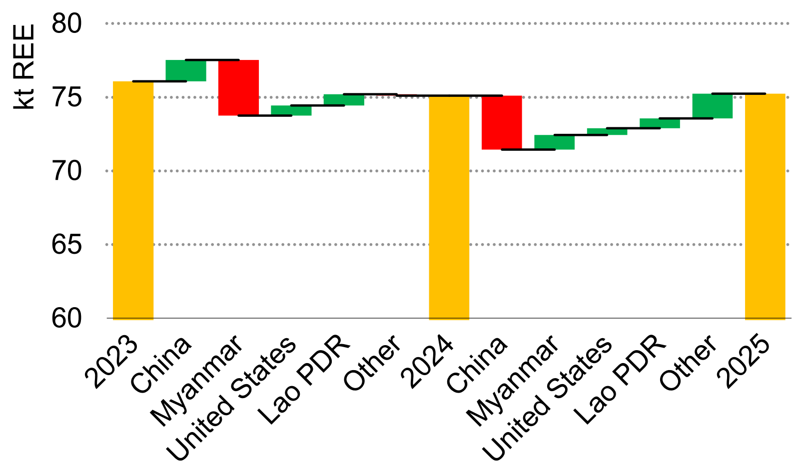
China's rare earth quota and new product traceability system

As the world's largest supplier of rare earths across mining, refining and recycling, the Chinese quotas for domestic mining and refining activities not only affect global supply but also indirectly influence rare earth prices.

While the rapid development in EVs and wind power increased demand for rare earths over the past years, the pace of demand growth slowed somewhat in 2024. Coupled with slowing energy technology deployment in some markets, the uncertainty in the global economic situation has resulted in an overall weak market. To align with these market shifts, China's rare earth quota was revised in 2024, with an under 6% increase in the mining quota, in sharp contrast to the over 20% surge seen in previous years. Stepping into 2025, downstream demand is expected to resume its growth, partly helped by anticipated interest rate reductions in various regions. If the production quota persists at the same level this year, coupled with the ongoing conflict in Myanmar, it could exert a substantial impact on the heavy rare earths market.

In addition, in April 2024, China issued the Rare Earth Management Regulations, which set out various rules regarding the exploitation, management and use of rare earths in China. In particular, the regulations provide for the creation of a new "rare earth product traceability system" under the supervision of China's Ministry of Industry and Information Technology (MIIT). In February 2025, the MIIT issued an additional draft regulation for public comment to further implement the new traceability system. The new system could enable the Chinese government to better track illegally mined or smelted rare earths, to increase control over supply and pricing, and to enhance the effectiveness of Chinese sanctions by monitoring flows of products containing rare earths. In addition, on 4 April 2025, China announced the implementation of export controls on seven medium and heavy rare earth-related products (see Box 2.2).

Changes in regional mined supply for magnet rare earth elements



Notes: REE = rare earth elements; Lao PDR = Lao People's Democratic Republic. The figures are for magnet REE only.

Box 2.2 China announced export controls on seven medium and heavy rare earths

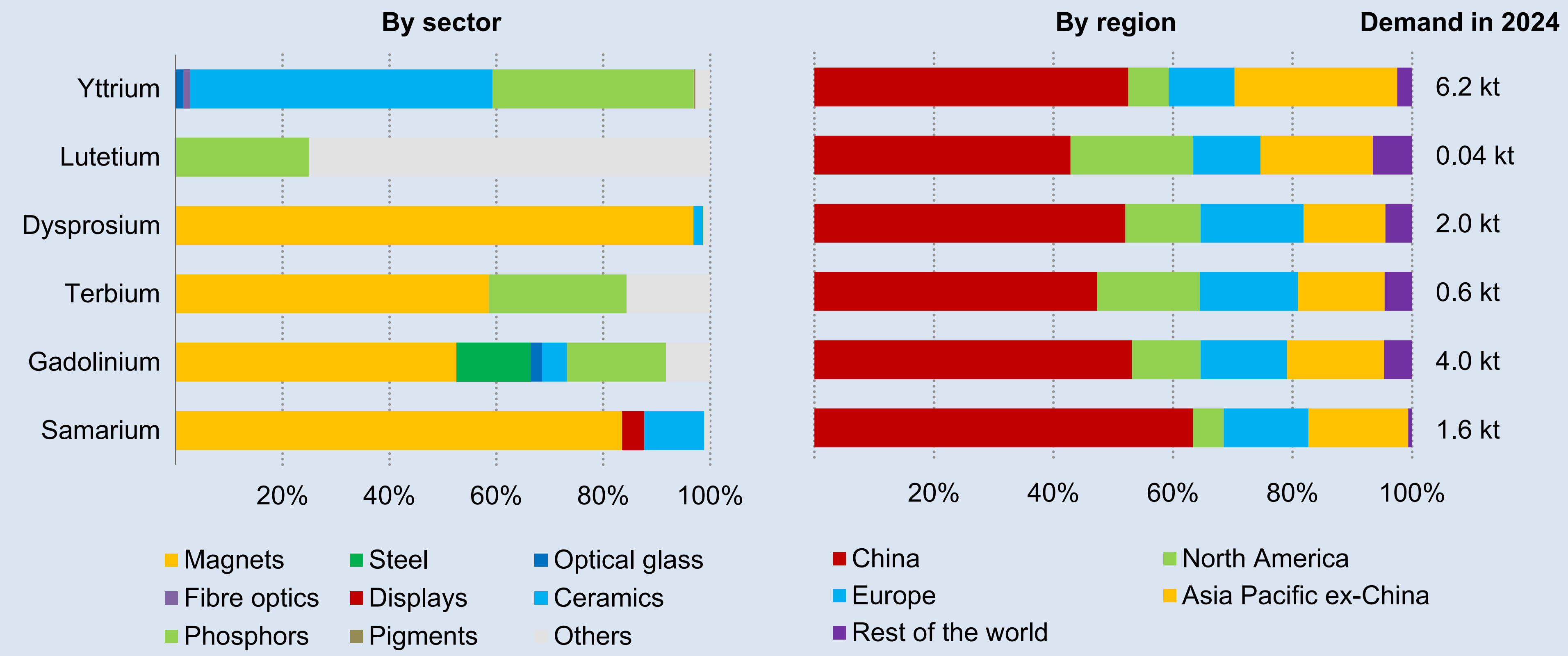
On 4 April 2025, the Chinese government (the Ministry of Commerce, and the General Administration of Customs) announced the implementation of export controls with immediate effect on seven medium and heavy rare earth-related items: samarium (Sm), gadolinium (Gd), terbium, dysprosium, lutetium (Lu), scandium (Sc) and yttrium (Y). Under these new regulations, exporters must apply for a permit through the Ministry of Commerce in accordance with the relevant provisions of the Export Control Law and the regulations governing the export of dual-use items. Exporters are required to strengthen product identification and specify in their customs declaration whether the items are subject to export restrictions.

Besides dysprosium and terbium, which are used in neodymium iron boron (NdFeB) magnets with applications in energy technologies, the export controls also target rare earths with applications in the production of ceramics, phosphors, steel, optical glass and fibres, and aerospace (samarium-cobalt or SmCo magnets). For four out of the seven elements (Sm, Gd, Tb, Dy) placed under the export controls, 55-95% of demand in 2024 was driven by their use in magnet manufacturing. By region, China was the largest demand centre for all the elements in 2024. Europe and North America together accounted for 20-35% of the demand for the elements most commonly used in magnets.

The export control announcement has not yet triggered a major surge in prices, as markets remain generally well-supplied and no immediate bans on export flows have been enforced. However, the move highlights the strategic importance of rare earth elements, and market dynamics could shift rapidly if actual disruptions to exports occur, or delays arise in approving export volumes to certain regions. The implementation of these controls could also affect efforts to build diversified magnet manufacturing supply chains, especially when coupled with the 2023 export ban on rare earth magnet manufacturing technology and equipment.

After the announcement of 90-day pause for higher tariffs between the United States and China in May 2025, it is expected that the process for obtaining export licences might be relaxed although the exact impacts remain to be seen. Mitigating the impacts of export controls will require short-term measures, but long-term resilience ultimately depends on co-ordinated efforts to develop diversified supply chains beyond the current leading producers. Promoting alternatives to rare earth-based technologies is another way to help mitigate the impacts of potential disruptions.

Demand for the rare earth elements under export controls by sector and region, 2024



Note: For scandium, the demand in 2020 was around 9 tonnes with major uses being in solid oxide fuel cells, aluminium alloys and defence equipment.

Australia leading efforts to step up financing

Australia has made substantial financing commitments to develop rare earth supply chains. In 2023, Australia established the AUD 15 billion National Reconstruction Fund (NRFC) and committed AUD 1 billion of the fund to the focus area of resource value addition. In January 2025, AUD 200 million (USD 126 million) of this fund was invested in Arafura Rare Earths as an equity investment, to support the development of Arafura Rare Earth's mine and processing facility in the Northern Territory. This comes in addition to the AUD 840 million (USD 554 million) worth of loans and grants to Arafura throughout its development. As of December 2024, the Australian government has also provided a total of AUD 1.7 billion (USD 1.1 billion) of funding to Iluka Resources from the AUD 4 billion (USD 2.5 billion) Critical Minerals Facility, to develop Australia's first fully integrated rare earths refinery.

In November 2024, Lynas Rare Earths opened the Kalgoorlie Rare Earths Processing Facility in Western Australia, marking a significant milestone as the country's first rare earth processing facility, producing up to 68 kilotonnes per annum (ktpa) of mixed rare earth carbonate Lynas Rare Earths has also announced plans to build a light and heavy rare earths separation facility in the United States to process feedstock from its Mt. Weld mine, supported by a total of USD 258 million in funding from the US government. The project was the recipient of an AUD 20 million (USD 14 million) Australian Government Modern Manufacturing Initiative grant in 2023.

In the United States, MP Materials is operating an LREE separation facility near its Mountain Pass mine since late 2023, constructing an HREE separation plant and is also expanding its footprint towards the downstream value chain by constructing a metal and magnet plant in Texas. Both Lynas and MP Materials' projects have received financial support from the US government, with the Department of Defense (DOD) granting awards to these projects to separate rare earths. The United States has also committed financing to other Australian projects: in 2024, the US Export-Import Bank signed a USD 600 million non-binding Letter of Interest with Australian Strategic Materials to help progress the Dubbo project in New South Wales and awarded USD 250 million in preliminary support to the Meteoric Resources project in Brazil.

While these are good signs for the diversification of supply, the complex separation processes of rare earth elements demand high technical standards and substantial research and development (R&D) investments. China holds a distinct advantage in rare earth separation technology (see Chapter 3), while other countries face certain technological gaps. What also remains to be seen is whether the diversified rare earths sources will be able to compete on costs with supplies from incumbent players.

Impacts of tariffs from the United States

Following an announcement by China's Ministry of Commerce prohibiting the export of rare earth magnet technology and equipment (including technology for extraction, separation, production of metals and alloys, and production of NdFeB magnets) in December 2023, the United States has made a series of announcements levying import tariffs on Chinese rare earth products with a view to reduce today's high levels of import dependence.

As of 4 February 2025, the United States imposed import tariffs on NdFeB permanent magnets and alloys (12.1%), NdPr, Dy and Tb oxides (10%), and rare earth metals (15%) produced in China, covering almost the entire supply chain for rare earth permanent magnets. These tariffs on Chinese products come on top of pre-existing tariffs of 2.1% on NdFeB magnets and alloys and 5% on rare earth metals originating from any country outside the United States. More recently in April 2025, the United States announced further tariffs on Chinese goods (largely excluding raw minerals but including final products) amounting to a total tariff of 145% on goods such as permanent magnets. These tariffs were later diminished to 30% for 90 days in May. It is unclear whether these tariffs will decrease or increase after the end of the three-month pause, but a base-level tariff of 25-30% on permanent magnets is expected to continue based on previous announcements. Moderate import tariffs may help boost the competitiveness of several early-stage projects within the United States but also in other magnet-producing regions such as the European Union (particularly Germany and Estonia), Japan, Thailand, Korea, India and elsewhere. Original equipment manufacturers (OEMs) such as General Motors have signed binding long-term supply agreements with E-Vac and MP Materials to source US-produced magnets for their cars.

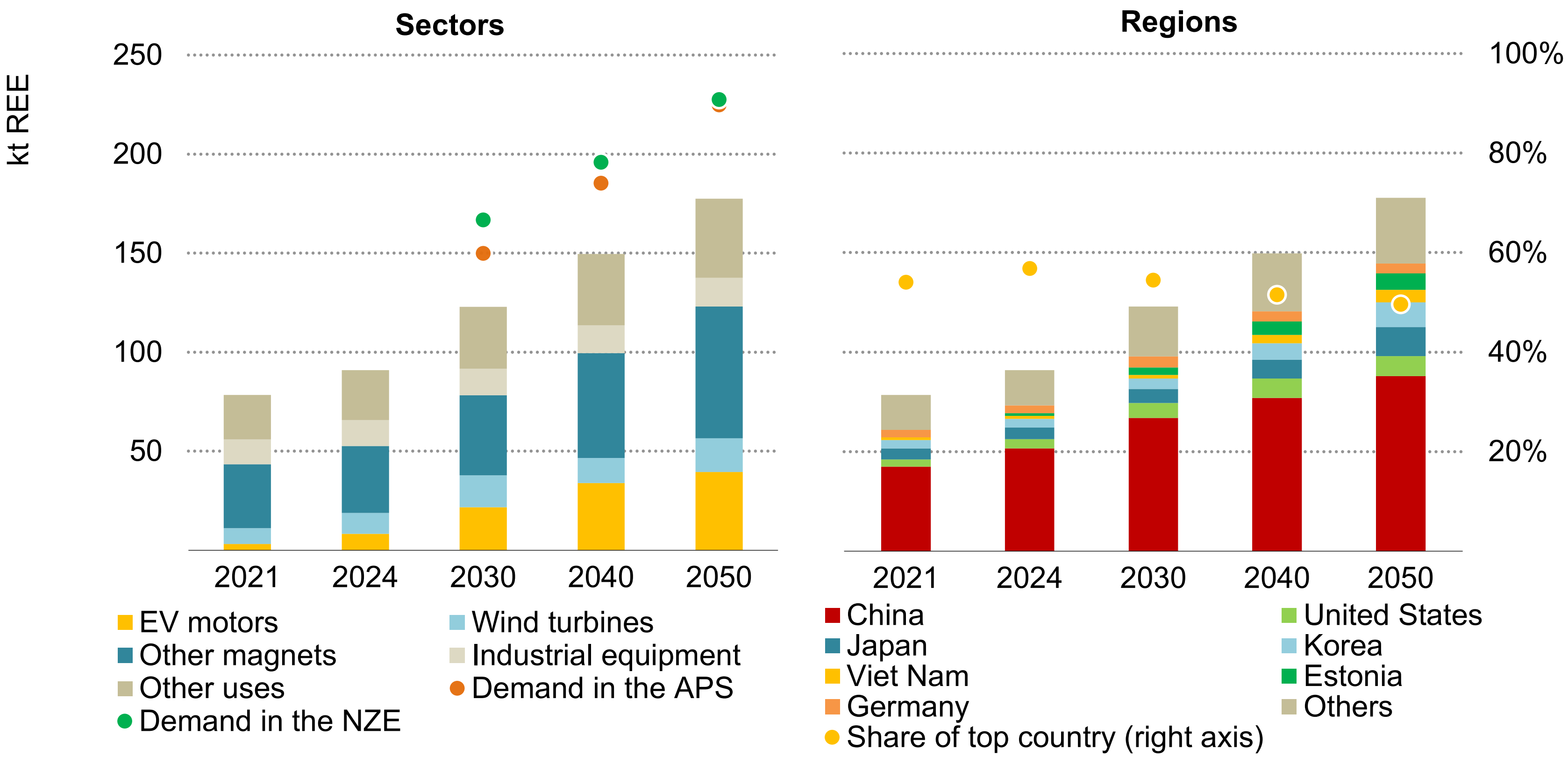
It is noteworthy, however, that due to the export controls (see box 2.2) announced by China on 4 April 2025, shipments of the affected minerals, including dysprosium and terbium, which are used in NdFeB magnets, have been halted until the licences are obtained. On the other hand, a retaliatory tariff of 125% announced by China on 12 April on all imports from the United States has led to an abrupt pause in the export of MP Materials' rare earth concentrates to Chinese refiners. As China accounts for the majority of the world's supply of separated HREEs such as dysprosium and terbium, these developments can severely hamper efforts to build diversified magnet supply chains. On 12 May 2025, the announcement of a 90-day tariff truce between the United States and China may be signal for further dialogue and negotiations.

Increasing attention on recycling of permanent magnets

In the context of supply security and diversification goals for rare earth elements, whose mining and processing remains one of the most geographically concentrated among energy minerals, the recycling of permanent magnets to create a secondary source of supply is increasingly emerging as a priority. 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. An alternative route for magnet recycling is gaining traction recently. For example, HyProMag, a UK-based start-up with its recycling facilities in the United Kingdom and Germany, and MagREEsource, a French start-up expanding recycling capacity, are advancing the Hydrogen Processing of Magnet Scrap (HPMS) technique. This process 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 environmental 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, Toronto-based Cyclic Materials that received USD 2 million from Jaguar and Land Rover in early 2025, and the Ionic Technologies pilot project in Belfast, are receiving support from major companies, providing further positive signals. Beyond automakers, one of Europe's largest electricity providers, Vattenfall, recently announced a commitment to create a 100% circular outflow of permanent magnets from its wind farms decommissioned from 2030 onwards – a move that could support efforts to scale up rare earth recycling.

Demand: Global demand for magnet rare earth elements nearly doubles by 2050; China remains the largest source of demand due to its strong position in permanent magnet manufacturing

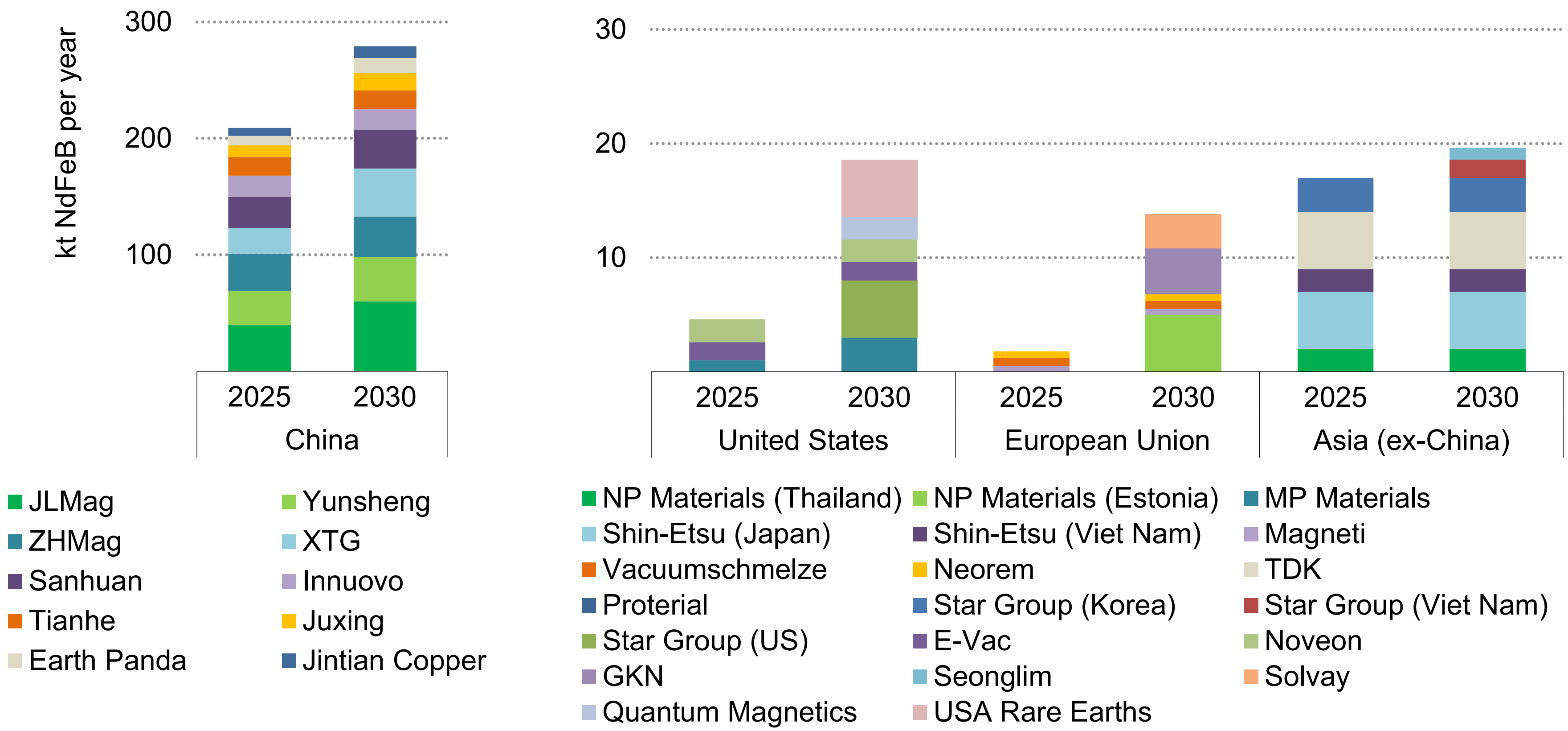
Outlook for the demand of magnet rare earth elements by sector and region in the STEPS



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

Demand: Permanent magnet manufacturing is led by China, but several new players are emerging

Expected annual production capacity for neodymium iron boron (NdFeB) permanent magnets



Note: The list of projects is indicative of future magnet production capacity based on today's announcements, it is not meant to be exhaustive.
Source: IEA analysis based on Project Blue.

Demand: Permanent magnets, including those in EV motors and wind turbines, drive demand growth

Sectoral trends

The global demand for magnet REEs (neodymium, praseodymium, dysprosium and terbium) has nearly doubled in the decade since 2015 to cross 90 kt in 2024, while the share of clean energy technologies, driven by new EV sales and wind turbine deployments, has expanded from just 8% to over 20% during the same period. In the STEPS, we see total magnet REE demand crossing 120 kt by 2030 and reaching 180 kt by 2050. A faster deployment of energy technologies in the APS and the NZE Scenario leads to demand crossing 130 kt and 145 kt respectively in 2030. EV motors significantly increase their contribution to demand growth with their share growing from 9% in 2024 to 22% in the STEPS and around 25% in the APS and the NZE Scenario in 2050. Driven by growth in deployment of EVs, wind generation and other applications, permanent magnets account for the majority of magnet REE demand growth, with their share rising from 60% today to around 70% by 2050 in all scenarios. Manufacturing of industrial equipment, glass, ceramics, microchips, use in catalysts and robotics (after 2040) make up the remaining demand.

Regional trends

As the largest producer of NdFeB permanent magnets (that use NdPr compounds along with iron and boron, as well as Dy and Tb as performance-enhancing additives), China is consequently the largest demand centre for magnet REEs. In 2024, China accounted for around 57% of the global demand for magnet REEs. This share falls to around 50% in 2050 as other players enter the permanent magnet manufacturing sector and demand from other uses grows in many regions. Some of the largest magnet manufacturing projects added globally are still in China, but the United States and the European Union see significant increases in production capacity in the coming decades as well.

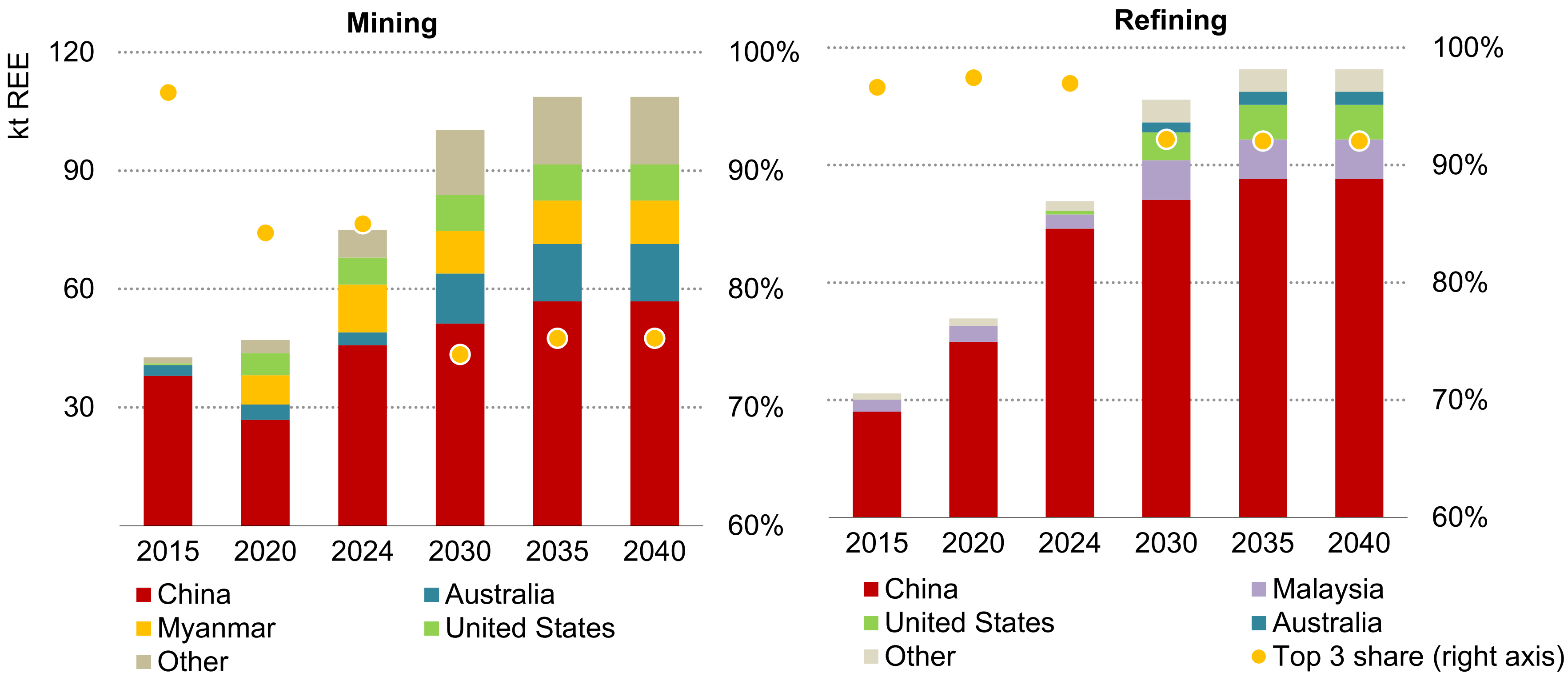
Compared with two decades ago, when China accounted for around 50% of the production of sintered magnets (most commonly used in EVs and wind turbines) and around 45% of the production of bonded magnets (used in appliances and electronics), its share in the production of these magnets has expanded massively to reach 94% and 80% respectively in 2024. China's exports of permanent magnet materials and rare earth compounds both increased year-over-year in 2024, around 28% for magnets and 15% for compounds.

Beyond magnets, China is also home to other major industries that use rare earths, such as catalysts, microchips, glass and ceramics. Japan, which accounted for nearly half the production of sintered permanent magnets in 2005, still remained the second-largest producer as of 2024 even though its share had fallen to around 5% of global production. Other notable producers of (mainly small, bonded) permanent magnets have been Germany, Russia, India, Korea, Viet Nam and Thailand.

Looking ahead, China leads new production capacity additions for permanent magnets based on announced projects that are slated to increase production in 2030 to around 300 ktpa of NdFeB. The European Union is set to increase magnet production to around 15 ktpa by 2030. Estonia emerges as a new producer in Europe by 2030 due to the mine-to-magnet manufacturing facility by Neo Performance Materials starting production in 2025. The Solvay project in France and the GKN Powder Metallurgy project in Germany add the remaining production capacity increase to 2030 in the European Union. The United States emerges as a major producer of sintered NdFeB magnets during the outlook period owing to several announced projects and new policies, reaching a production capacity of nearly 20 ktpa and becoming the second-largest magnet manufacturing country by the next decade.

Supply: Geographical concentration for mining sees slight improvements, but refining remains the most concentrated of all critical minerals

Magnet rare earths production from operating and announced projects in the base case



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

Supply: Refining remains in very few hands, but China's share declines gradually as diversified projects come online

The supply of magnet REEs remains among the least geographically diversified of all critical minerals. In 2024, the share of the top three producers for mining stood at 86%, of which China alone accounted for 60% of global mined production. For refining, the top three countries controlled the lion's share (97%) of the refined output in 2024, with China's dominance even more pronounced than in mining as it single-handedly represented 91% of the refined output.

On mining, 45% of global mined total REE production in 2024 came from the Bayan Obo mines in China. In the rest of the world, Mountain Pass (MP Materials) in the United States and Mount Weld (Lynas) in Australia are leading production sites. The two fastest-growing regions in terms of mined REE production in the last decade have been Myanmar, which grew its share in global production from just 0.2% to 16%, and the United States, growing from 1% to 9% in the same period.

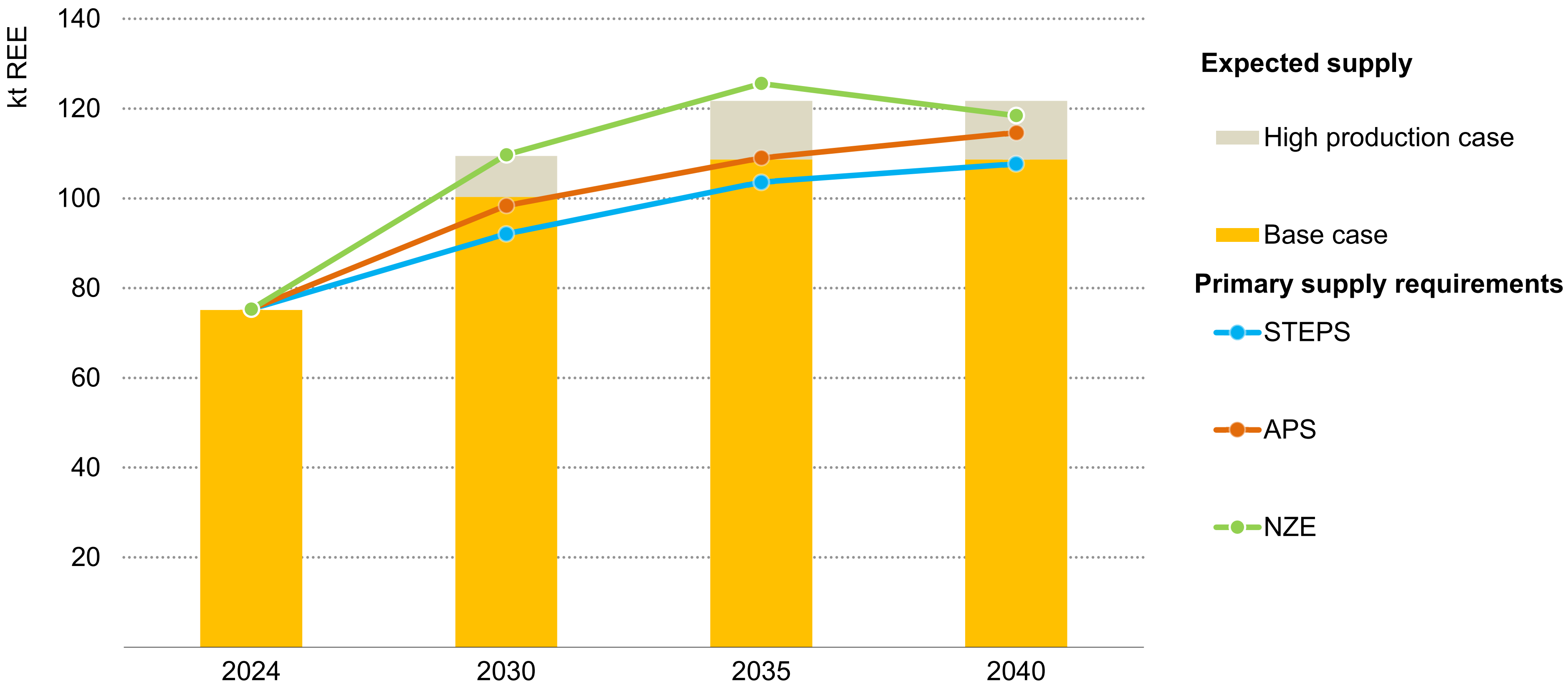
The expected supply of magnet REEs from operating and announced mining projects in the base case rises by over 50% from today's levels reaching around 110 kt in 2040. Including several early-stage projects as analysed in the high production case, mined REE supply can be 13 kt higher in 2040. While China and Myanmar remain two of the leading producers throughout the outlook period, a slight dampening of their production growth rates causes the share of the top three countries to be lower compared with last year's Outlook, falling to around 76% in 2040. Today, the fourth-largest mined supplier, Australia, enters the list of top three producers within a decade as a majority of announced projects slated to come online globally (Iluka, Astron Energy Fuels, Arafura Rare Earths) are located in the country.

On refining, Chinese dominance in 2024 remained difficult to challenge. In the rest of the world, refineries owned by Lynas in Malaysia, MP Materials in the United States, Viet Nam Rare Earth JSC (VTRE) in Viet Nam (which has faced several judicial hurdles since 2023) and Neo Performance Materials in Estonia (Silmet) are the notable industrial-scale producers.

The expected refined supply from operating and announced projects in the base case rises to 106 kt in 2030 and 115 kt in 2040, with the share of the top three refining countries remaining high, falling only marginally from 97% today to 92% in 2030. China's share in refined output falls from 91% today to 75% in 2040. If several early-stage projects outside China, such as new projects by Tronox and Energy Fuels in the United States and Lynas' plant in Malaysia, come online as planned, China's share falls further to 73% in 2040, as in the high production case.

Supply: Expected supply nearly in line with requirements to 2030, but limited announcements of new projects and geopolitical events pose risks to security

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



Notes: REE = rare earth elements. The figures are for magnet rare earths only. Primary supply requirements is the demand net of reuse and recycling.

Implications: Redoubling efforts to support projects in diverse regions and promote innovation and recycling is vital for secure rare earth supplies

Demand-supply balance and secondary supplies

Broadly, the supply from today's operating projects has been sufficient to meet current demand, and this is likely to be the case for the next few years. The balance could be affected if the current situation in Myanmar continues for the rest of 2025, depleting inventories of ionic adsorption clay (IAC) feedstocks for HREEs at Chinese refineries. Between 2025 and 2040, nearly 60% of the global increase in mined supply for all REEs come from today's operating mines.

If planned projects come online as scheduled, the projected supply for magnet REEs in the base case could meet the primary supply requirements (total demand net of secondary supply) in the STEPS over the projection period to 2040. In the APS after 2035 and the NZE Scenario after 2030, some gaps emerge between the base case supply and the primary requirements, which would require additional projects from the high production case to materialise.

The major concern for magnet REEs, however, is not the gap between demand and supply, as in the cases of copper or lithium, but rather a very high level of geographical concentration. This is already true today and remains the case for future mining and refining operations, exposing this market to price volatility and supply risks.

Growing secondary supplies from recycling post-2030 also help temper the growth of primary supply requirements. Primary supply requirements in the medium to long term are a function of growing interest in recycling of manufacturing scrap and end-of-life magnets that will generate secondary supplies. In 2035, around 38 kt of total magnet REE demand (27%) may be met using secondary supplies in the STEPS. Between 2035 and 2050, the secondary supply expands further to serve over 30% of total demand. The shares of secondary supply rise further in the APS and the NZE Scenario, to 35% and 39% respectively in 2050.

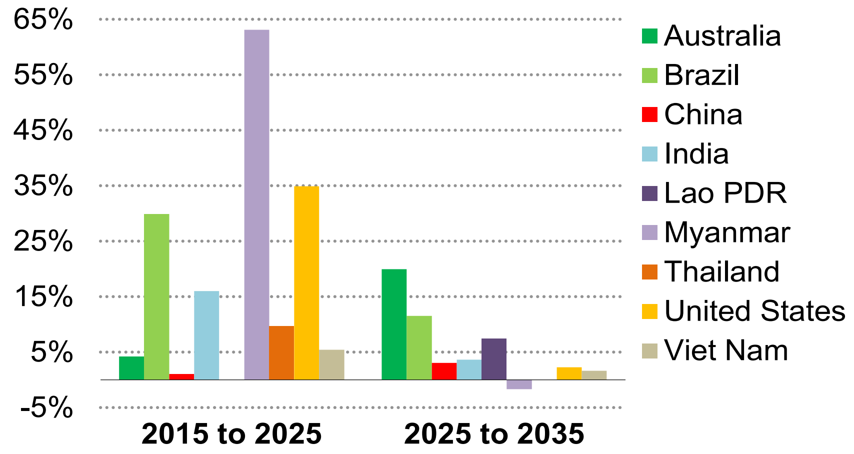
Successful rare earth recycling efforts will hinge on synergies with either rare earth magnet producers or primary miners and refiners. A wide range of policies can positively support recycling economics. These include lowering the cost of accessing scrap through standardised labelling, implementing extended producer responsibility schemes to support collection efforts, setting material-specific recycling targets and encouraging the purchase of recycled materials. As mentioned before, recycling of permanent magnets is gaining momentum in regions with low resource endowment, such as the European Union. While this is a positive sign, investment in new and diversified primary supply sources will still be needed to securely meet future demand.

Prospects for diversified supplies

Diversification in the rare earths market has been limited by several factors. In the upstream segment, only a handful of mines (in the United States, Australia, Viet Nam and Brazil) are operating at scale today outside China and Myanmar. On average, newly announced projects have a lead time of eight years, making the scaling up of mined production beyond the incumbent producers a challenging proposition. Furthermore, the separation process for rare earths (see Chapter 3) and their refining are fairly complex and require significant amounts of investment in technology. The refining segment of the supply chain outside China is even more nascent than mining, with only a couple of industrial-scale facilities operating today in Malaysia, the United States and Estonia. There are improvements expected on the horizon with major refining units starting or nearing operation in Australia, the United States and France. International partnerships like the one between France and Japan for the Caremag project, where Japan will invest EUR 110 million and sign a long-term offtake contract to secure half of the HREE oxide output from the project, also provide avenues for diversification. So far, China has had both a technological and a cost advantage over other regions, but this could change with strengthened efforts to promote technology innovation and provide financial support to de-risk projects.

Another consideration is regarding the type of ores that magnet REEs often come from, i.e. heavy sands (monazite sands), which also contain radioactive elements such as uranium and thorium, and very few countries have the infrastructure to use or store these by-products. 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. Appropriate waste management performance will be vital to scaling rare earth supply chains in geographically diverse regions.

Average annual growth rate for mined magnet rare earths supply by country



Note: Lao PDR = Lao People's Democratic Republic.

Brief review of other materials

Aluminium

Aluminium traded at the London Metal Exchange (LME) at a range of USD 2 116 per tonne to USD 2 721 per tonne over the past year. This volatility was driven by multiple factors including disruptions in raw material supply, macroeconomic policies and geopolitical developments. Alumina prices surged more than 130% in 2024 to reach historic highs, following the suspension of refinery operations in Australia and a bauxite export disruption in Guinea. In addition to supply-side constraints, foreign exchange fluctuations, interest rate policies, and the imposition of sanctions and tariffs further influenced market dynamics.

Demand for aluminium continues to grow, supported by both conventional uses in construction and manufacturing sectors and expanding applications in energy technologies. These include solar photovoltaic (PV), EVs and power transmission infrastructure.

On the supply side, Chinese policies remain a critical factor. The primary production cap of 45 Mt was initially imposed in 2017 to avoid overcapacity and reduce emissions. Total production capacity reached this ceiling in 2024. Ongoing droughts in China pose a risk to hydro-powered aluminium production, potentially leading to temporary output cuts and increased production costs.

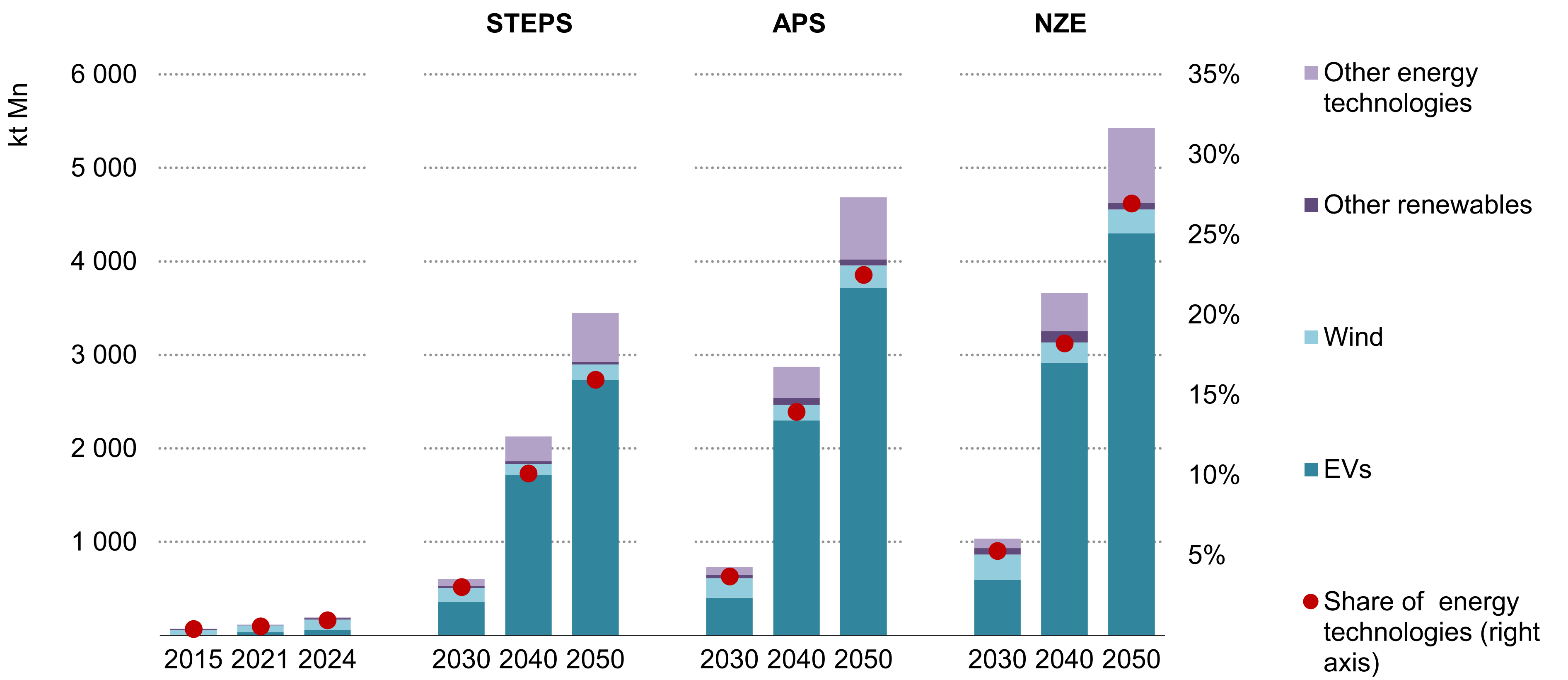
China's decision to abolish its export tax rebate on aluminium products in December 2024 may reduce outbound supply, impacting global availability. On the other hand, new smelting capacity is expected to come online in the near term, and alumina shortages are anticipated to ease as production ramps up in India and Indonesia.

Geopolitical developments continue to impact the aluminium supply chain. The European Union's 16th sanctions package includes a direct import ban on Russian aluminium, while the United States has increased import tariffs from 10% to 25% for all countries except Russia, which has been subject to 200% tariffs since early 2023. The potential of these moves to incentivise the restart of underutilised domestic smelting capacity in both regions depends heavily on prevailing market prices and input costs.

Aluminium production is highly energy-intensive and emits significant carbon emissions. Primary aluminium can emit up to 16 tonnes of CO_2-equivalent (tCO_2-eq) per tonne, while secondary aluminium emissions are significantly lower at approximately 0.5 tCO_2-eq per tonne. Increasing the use of recycled aluminium presents a clear path to reducing industry emissions.

Manganese: The growth in manganese in EV batteries drives a surge in demand for battery-grade manganese sulphate, which is almost entirely supplied by China

Manganese demand in energy technologies by scenario

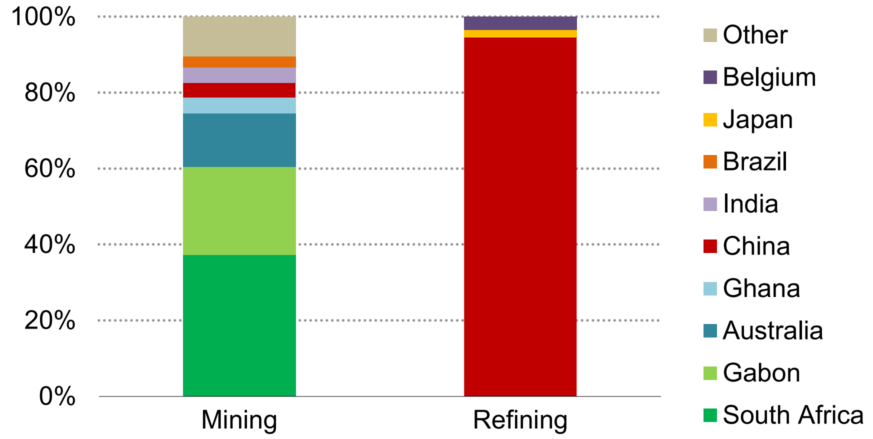


Manganese

Manganese demand is primarily driven by its essential role in steel alloys. While currently a small portion of total demand, the use in batteries is growing rapidly due to manganese's importance in key EV cathode chemistries – namely lithium nickel manganese cobalt oxide and more recently lithium iron manganese phosphate (LMFP), a higher-energy-density variant of conventional LFP chemistry now entering the market. Manganese-rich cathode chemistries such as lithium nickel manganese oxide are also emerging. A critical issue for manganese is that batteries require a specific type of manganese – battery-grade, high-purity manganese sulphate, which is highly concentrated in its production. This battery-grade manganese sulphate is used to produce pCAM and then the various cathode materials.

By 2030, manganese demand from energy technologies more than triples in the STEPS and grows over fourfold in the APS. By 2050, manganese demand from energy technologies is 20 times higher than today in the STEPS. The rapid growth in EV deployment and of manganese-rich chemistries is responsible for this exceptional growth in manganese demand. This results in the share of demand from energy technologies increasing from 1% today to over 15% in 2050 in the STEPS and almost 25% in the APS. Steel remains the dominant source of manganese demand, but the growth is increasingly driven by high-purity manganese sulphate for batteries.

Geographical distribution of manganese mining and refining



IEA. CC BY 4.0.

Note: Refining refers to production of battery-grade high-purity manganese sulphate monohydrate.
Sources: IEA analysis based on USGS (2025), Minerals Commodity Summaries 2025, and Benchmark Mineral Intelligence.

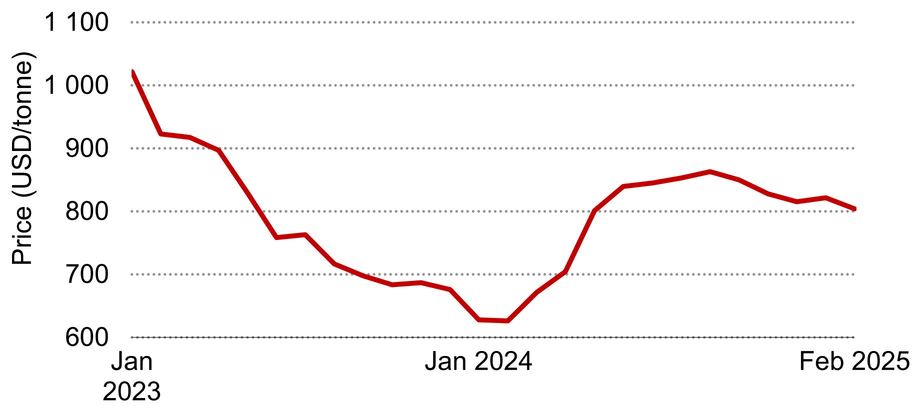
Mined supply of manganese is not a key constraint as is the case for other battery metals. Its supply is concentrated with the top three countries producing three-quarters of supply in 2024, though it remains more diversified than nickel or cobalt. South Africa is the leading supplier, accounting for almost 40% of global supply in 2024, followed by Gabon with almost a quarter and Australia with 15%. While high-purity manganese sulphate can be produced from both carbonate and oxide ores, purity significantly affects refining costs.

Higher-grade ores, predominantly found in Gabon, South Africa, Brazil and Australia, are most sought after as they contain less impurities thus requiring less additional processing. Higher-grade oxide ores are less abundant and more geographically concentrated, whereas lower-grade carbonates are more widely distributed. Higher-grade ores made up around a quarter of production in 2024.

Supply of high-purity manganese sulphate reached 90 kt in 2024 with 95% supplied by China, demonstrating the extreme concentration of supply. There are only two other refineries in Belgium and Japan producing high-purity manganese sulphate, together producing the remaining 5%. At the start of 2024, significant excess capacity together with increased raw material costs (ore, sulphuric acid and caustic soda) led to production cuts and maintenance shutdowns in China. This caused prices for battery-grade manganese sulphate to increase in 2024, reaching as high as USD 860/tonne. Battery-grade manganese sulphate prices outside of China are much higher due to higher capital and operating costs, limited economies of scale and more stringent sustainability requirements. For instance, the capital intensity of Element 25's project in the United States was reportedly more than double that of Firebird Metal's project in China.

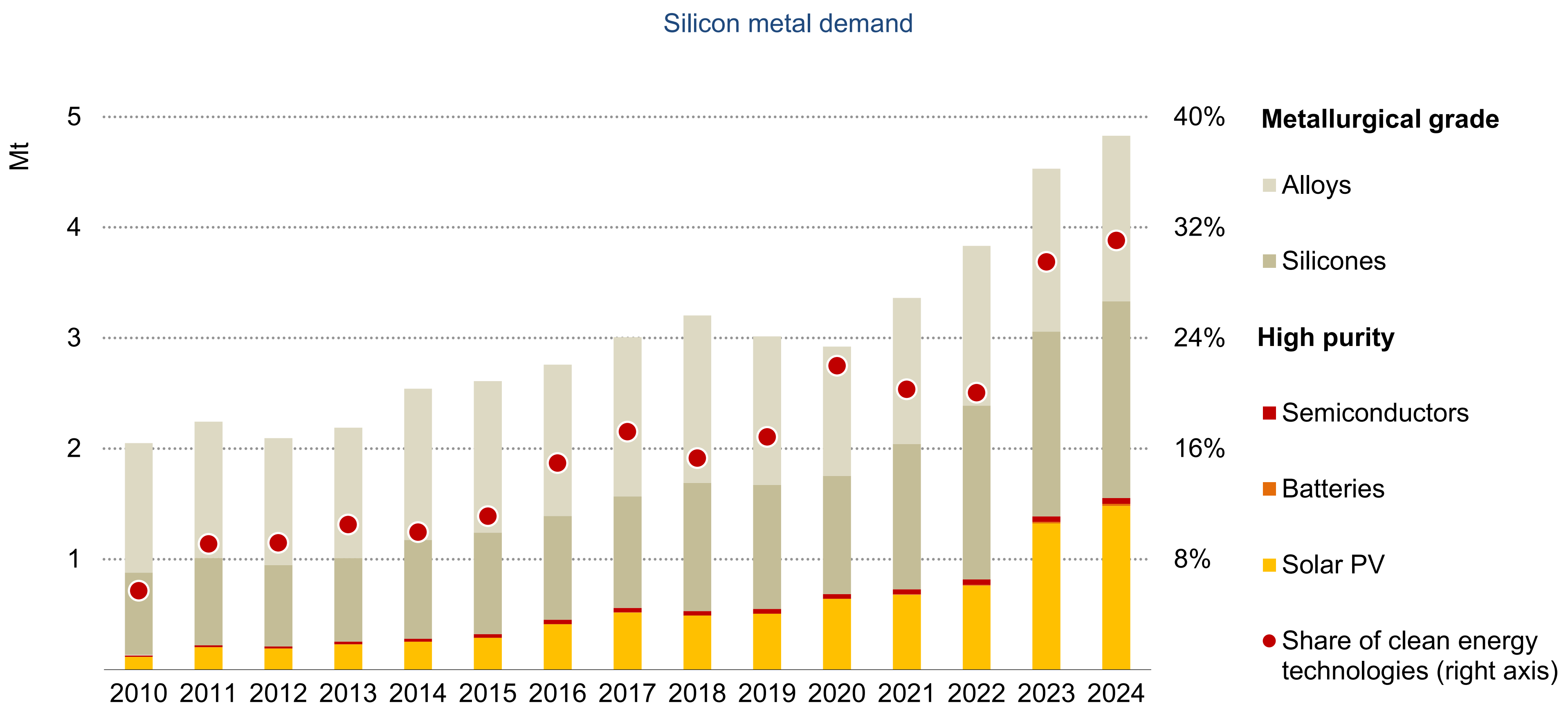
Significant capacity expansions are in development, driven by the anticipation of the surge in demand growth from EV deployment and the increasing adoption of LMFP. Almost 50 brownfield and greenfield projects have been announced, mainly in China, though there are announcements in other regions. The largest producer outside China, Vibrantz Technologies, plans to expand its sulphate capacity to almost 15 kt this decade beyond its existing operations in Belgium with a major new project in Mexico. MMC is planning to develop a 10 kt sulphate project in South Africa aiming to start operations by 2030. Despite these announcements, many analysts expect a deficit in the supply of battery-grade manganese sulphate as early as the early 2030s. The development of manganese recycling capacity from end-of-life batteries will become increasingly important if these deficits materialise. Nevertheless, there are significant challenges to scaling production in other regions due primarily to the significant capital and operating cost disparities with China.

Price of battery-grade manganese sulphate



Note: Mn sulphate 32% Ex Works China.
Source: IEA analysis based on Bloomberg.

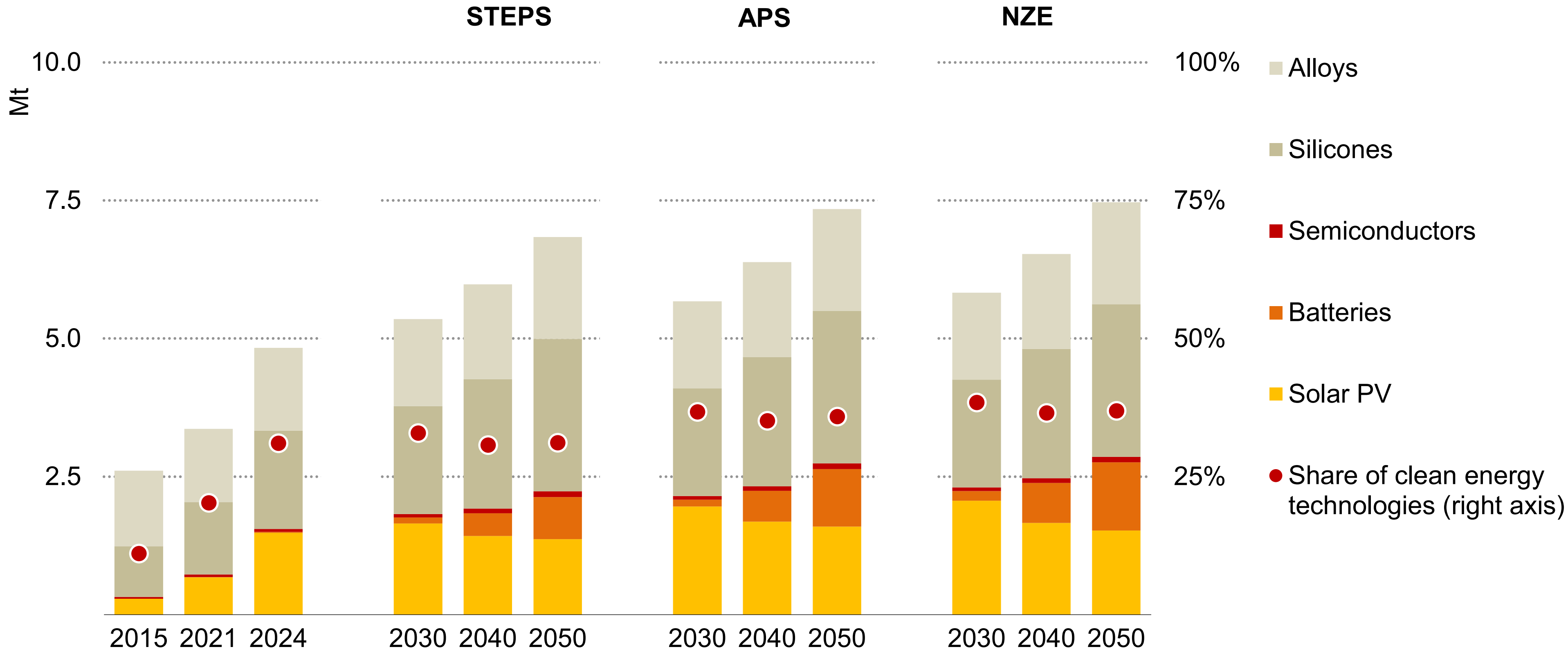
Silicon: Rapid deployment of solar PV technologies in recent years has driven a step change in demand for high-purity silicon



Note: Silicon metal = generally accepted trading name for elemental silicon refined in its metalloid form, covering both metallurgical grade and higher purity grades.

Silicon: As solar PV demand stabilises due to material efficiency, EV batteries play an increasing role in driving future demand growth for high-purity silicon in anodes

High-purity silicon metal demand outlook by sector and scenario



Note: High-purity silicon includes both polysilicon for solar PV and semiconductor applications as well as silicon in battery applications.

Silicon

Two successive energy sector demand drivers: Solar PV and battery anodes

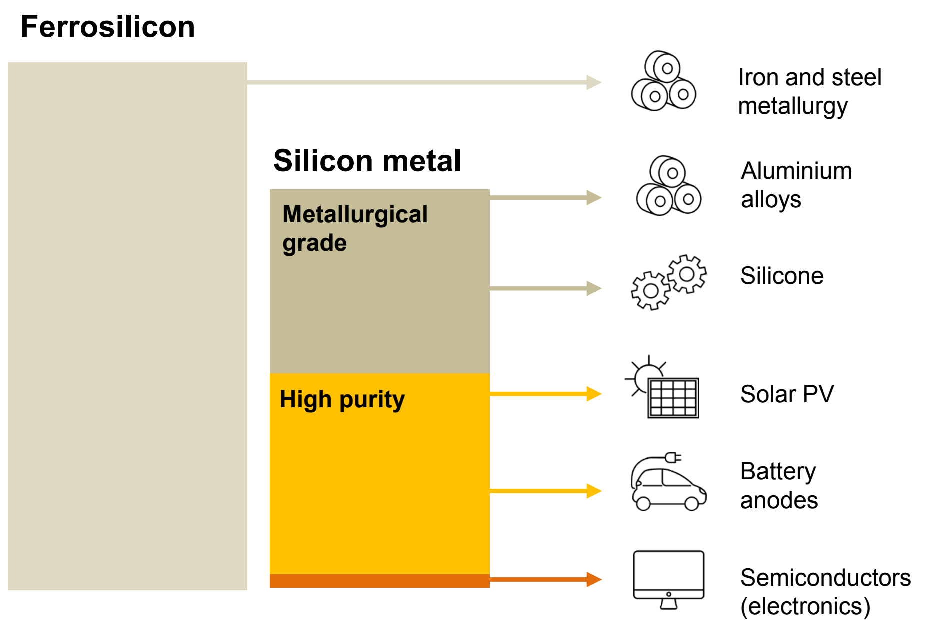
The silicon market is set for two distinct waves of demand growth, both driven by energy technologies. The first wave stems from the rapid expansion of solar PV installations, which has more than doubled demand for high-purity silicon since 2020, reaching record levels.

Since 2010, the energy sector's share of silicon metal demand has risen from 6% to over 30%, significantly increasing the need for ultra-pure variants with impurity levels below 1 part per million. Today, solar PV accounts for over 95% of high-purity silicon demand, representing nearly a third of total silicon production. The remainder is used in EV batteries or processed into even purer forms for semiconductor manufacturing.

Looking ahead, the solar PV industry continues to dominate high-purity silicon consumption. However, improvements in panel efficiency, thinner wafers and reductions in material losses are expected to moderate growth, with demand peaking around 2030 at approximately 1 650 kt in the STEPS and 2 000 kt in the APS.

While solar PV-related demand reaches its peak, overall demand from the energy sector continues to grow, driven by increasing silicon use in battery technologies. Currently, around 15% of battery anodes already incorporate small volumes of silicon, and silicon requirements are expected to rise, with 35% of batteries containing medium to high levels of silicon by 2035. Although silicon demand from batteries remains relatively low today, it is set to grow rapidly, surpassing 100 kt by 2030 and reaching 750 kt by 2050 in the STEPS. As battery demand rises and solar-related demand peaks, the share of energy technologies in total silicon metal demand remains stable at around 30% throughout the projection period.

An overview of applications for silicon



High-purity silicon production capacities rise, but supply remains vulnerable due to geographical concentration

Supply concentration risks are greater in refining than in mining. Today China is responsible for around 70-80% of global silicon metal production. While silicon is the second-most-abundant element in the Earth's crust, producing high-purity silicon metal requires highly pure quartzite or silica, which still depends heavily on specialised refining processes.

Large-scale high-purity silicon manufacturing capacities are being developed to support the growth of solar PV, but these capacities are highly geographically concentrated. In 2024, global production capacity reached 1 900 kt, with 95% of production coming from China, followed by Germany (50 kt), Malaysia (23 kt) and the United States (16 kt).

A few notable projects are being developed in more geographically diverse regions, such as OCI TerraSus' plant in Malaysia, whose announced capacity is set to reach 56 kt. This plant's development was accelerated in response to strengthened US import barriers on solar PV products containing silicon sourced from western China. A large-scale 100 kt project has also been announced in Oman. However, some manufacturing capacities outside of China are shutting down, most notably REC Silicon's plant in the United States.

Emerging silicon metal secondary supply in Europe

The recycling of solar PV panels remains a nascent industry, hindered by the high costs of waste collection and the relatively low concentration of metals. Recyclers typically focus on bulk or precious materials in solar panels, such as glass, copper, aluminium or silver. However, policy interventions, most notably extended producer responsibility schemes, are now helping to support the industry in Europe, making less lucrative recycling processes more viable. In 2024, dedicated solar silicon recycling facilities began ramping up production in Europe, reaching an initial capacity of 3 kt in France. The industry aims to reach 40 kt in France, 30 kt in Germany and 10 kt in Spain. Recycled materials currently reach 5N (0.99999%) purity, which is insufficient for solar PV applications but sufficient for metallurgical uses. Additionally, significant R&D funding provided by the Korean government may help make recycling of silicon from EV batteries viable.

Platinum-group metals

Primary supply

Prices for the five platinum-group metals (PGMs) – platinum, palladium, rhodium, ruthenium, iridium – traded within a fairly narrow band in the past 12 months. Rhodium and ruthenium prices showed signs of recovery in early 2025, but prices for palladium and platinum remained subdued despite persistent deficits, weighed down by expectations of weak demand across several sectors.

In 2024, South Africa, the world's leading producer of PGMs, experienced a decrease in mine production compared with 2023. This was largely due to a combination of low PGM basket prices, rising operating costs and widespread restructuring efforts. Although refined output increased year-on-year due to processing of work-in-progress material, this trend is unlikely to continue.

The supply outlook remains structurally challenged. Many South African underground operations are now operating at or below break-even, with little relief expected from input cost inflation or exchange rate movements. As a result, further asset rationalisation, including shaft closures, production curtailments, and capital expenditure deferrals, appears possible.

In North America, palladium-dominant operations face similar or greater pressures. High cost structures have already triggered production cuts and impairment charges, most notably at Sibanye-Stillwater's Montana complex, where annual output is set to decrease by more than a third in 2025.

On the other hand, Russian refined output, dominated by NorNickel, rose modestly in 2024 following smelter rebuilds and a recovery from constrained 2023 volumes. However, given the co-product nature of PGM production in Russia, supply remains relatively inelastic to price. Geopolitical risks continue to cloud the long-term outlook.

Persistently low prices for platinum, palladium and rhodium, which account for about 90% of the global market value for PGMs, will also impact the supply of the minor metals ruthenium and iridium. Although they are a small proportion of total production value, they are used in specialised chemical and catalytic applications including in hydrogen electrolysers and crucibles for crystal growth.

Secondary supply

Secondary PGM supply accounts for about 20-30% of total demand for platinum, palladium and rhodium. This makes recycling a critical component of global supply-demand balances, especially amid a tightening primary supply outlook in the medium term.

The automotive sector is the primary source of recycling feedstock through spent autocatalysts, but structural inefficiencies continue to limit recovery rates. Globally, over 30% of PGMs embedded in end-of-life vehicle catalysts are not recovered, largely due to inadequate collection systems and recycling infrastructure in smaller or late-stage markets. In contrast, PGMs used in industrial catalysts achieve much higher recycling rates nearing 95%, reflecting the more centralised recovery processes in these segments.

In 2024, secondary PGM supply is estimated to have stayed flat year-on-year, driven largely by China, where a trade-in programme for older vehicles is likely to have boosted recycling feedstock availability by targeting high-PGM-content vehicles. This initiative, however, is set to expire at the end of 2025. Decline in other regions was largely driven by macroeconomic and regulatory headwinds. In the United States, elevated used vehicle prices and high interest rates suppressed the scrappage rate, reducing the inflow of recyclable material. Further uncertainty was introduced by proposed federal legislation aimed at stamping catalytic converters with traceable vehicle identification numbers.

In Europe, despite mature and technically advanced recycling infrastructure, capacity utilisation was low due to persistent feedstock scarcity. Falling interest rates have yet to materially impact scrappage volumes, suggesting broader economic inertia and vehicle retention trends are dominating.

Demand

The automotive sector remains the primary end-use market for platinum, palladium and rhodium, accounting for about 45% of platinum demand and 85-90% for palladium and rhodium. However, global demand from this segment continues to soften.

Ongoing thrifting and substitution also continue to erode per-vehicle PGM loadings. In China, automakers have largely shifted to palladium over platinum in gasoline vehicles, driven by price parity and technical preferences. This trend has reduced platinum's share of autocatalyst demand in one of the world's largest auto markets.

Furthermore, although reductions in policy incentives for EV purchases provided temporary support for internal combustion engine and hybrid vehicle sales in the United States and key European markets, production of catalysed vehicles is likely to continue declining as EVs are set to account for more than 40% of car sales in 2030 under today's policy settings.

New uses of PGMs in hydrogen technologies, such as fuel cells and electrolysers, have not yet scaled significantly, with the hydrogen industry continuing to face significant headwinds.

Uranium

The uranium market experienced considerable volatility throughout 2024. In early 2024, prices for uranium concentrate (U3O8) surged to decade highs of USD 100 per pound due to heightened geopolitical risks and strong investor demand. However, prices declined to around USD 70/pound by year-end, returning closer to historical averages, due to near-term supply increases from Kazakhstan and Canada and broader macroeconomic pressures.

For years, global uranium production was constrained by underinvestment in primary supply and abundant secondary supply, but key suppliers ramped up primary output in 2024 to capitalise on high prices. Kazakhstan, the world's leading producer (40% of global supply), increased exports despite operational hurdles. Additional supply growth came from Canada, Namibia and Uzbekistan, while uncertainty persisted regarding Russian uranium exports due to geopolitical tensions.

However, supply expansion remains fragile. Many mines continue to face cost inflation, permitting delays and declining ore grades. While short-term production increases have helped ease spot market tightness, the long-term security of supply remains a key concern, particularly as many utilities across the globe seek to reduce reliance on Russia.

Meanwhile, global nuclear energy development continues, with China leading in new reactor construction and some European nations reassessing nuclear power's role in energy security. Advanced economies are also investing in small modular reactors, which could also contribute to long-term uranium demand.

Current projections suggest that existing uranium mines should be able to meet global demand in the near term. However, as nuclear capacity grows, uranium requirements will increase, necessitating efforts to bring idled mines back into service and develop new mines. As uranium supply is typically secured through long-term contracts that limit price volatility, volume security is likely to be required to support supply growth.

Ensuring a secure and affordable expansion of the nuclear sector also requires greater diversification of uranium supply and enrichment services. Uranium production is heavily concentrated, with just four countries accounting for around 80% of global mine output. Similarly, enrichment capacity is dominated by a handful of suppliers, with Russia alone responsible for over 40% of global uranium enrichment. Some countries such as the United States, United Kingdom, and France are planning to expand their enrichment capacities.

Silver

In 2024, silver prices rose from about USD 23 per troy ounce (toz) to USD 30/toz, and reached USD 34/toz in March 2025, the highest level in a decade. This was driven by the macroeconomic environment as well as growing demand from industrial sectors, especially solar panels.

Mine production of silver, which accounts for over 80% of a total supply of 1 billion toz, has declined over the past decade including in the past three years, which have seen prices above historical averages. Approximately half of the mined silver production in 2024 came from Mexico, China and Peru. Mexico, the largest supplier, saw a 2% increase in annual production, reaching 190 million toz as output from the Newmont mine in Peñasquito recovered following suspended operations for four months in 2023.

More than 70% of primary silver is produced as a co-product of copper, gold, lead and zinc, rendering supply less sensitive to prices. As a result, despite potentially elevated prices in the near term, supply may be challenging to increase structurally. However, recycled supply, which can be more price elastic, has increased from 14% of supply in 2015 to about 19% since 2022.

Global demand for silver was around 1.2 billion toz in 2024, down slightly from 1.3 billion toz in 2022. Industrial demand now accounts for almost 60% of total demand, up from less than 45% in 2015. The bulk of this increase was driven by demand for solar PV, which alone represents 17% of total silver demand. The 200 million toz of demand in 2024 for solar PV was 70% higher than in 2022 and more than three times the 2015 level.

Each gigawatt of solar PV capacity added today requires about 300-400 koz, or 10-13 metric tonnes, of silver. Although growth in global solar installations has far outpaced ongoing efforts to reduce silver intensities for solar panels, high prices are likely to accelerate R&D on lower-cost alternatives to silver in solar panel manufacturing.

Growth in demand from the solar sector over the past decade has more than offset declines in other areas, including physical silver investment, silverware and photography.

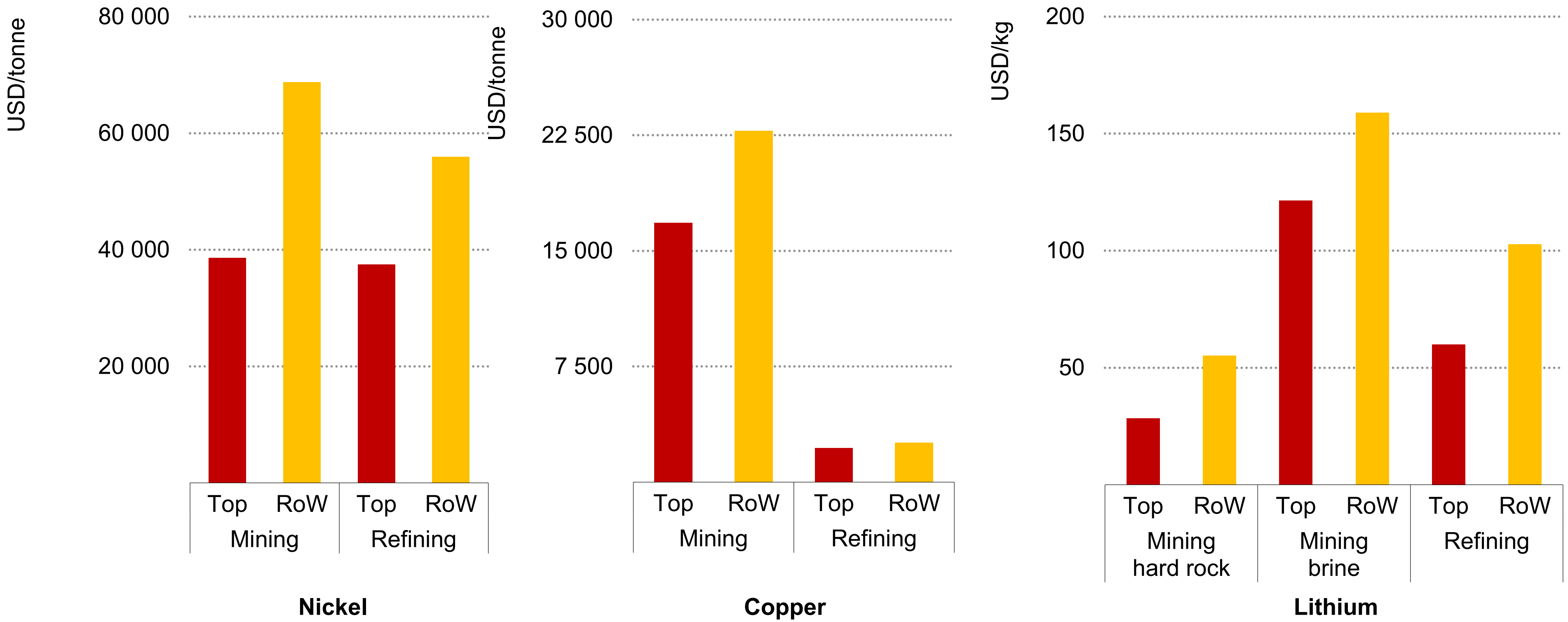
Beyond solar PV, silver is used in many energy and electronic applications due to its conductivity and durability. This includes sectors such as EVs and consumer electronics, demand for which are expected to continue increasing. Given the persistently high demand driven by increasing consumption from the solar PV sector and inelasticity of supply, today's market tightness appears likely to persist in the near term.

3. Topical deep dives

Policy mechanisms for diversified mineral supplies

The capital intensity of mining and refining projects outside the top producer is on average 50% higher

Typical capital intensity of mining and refining in the top producer versus the rest of the world for nickel, copper and lithium



Notes: RoW = Rest of world. Top refers to the top producer in that mineral and segment (e.g. Indonesia for nickel mining). Capital intensity data collected through company announcements and financial reports. Companies selected based on sample of the largest completed and planned projects across the world for each mineral. Capital intensities are estimated based on historical investment data. They do not account for declining ore grades, which may affect future capital intensities, particularly for established markets such as copper.

Key energy mineral operations in less-established producing countries face growing cost pressures, posing risks to diversification and sustainability efforts

Supply chains for key energy minerals are highly concentrated, creating strong incentives for policymakers to build more secure and resilient supply chains through greater diversification. However, as described in Chapter 2, progress has been relatively slow, and it has been difficult for new projects and new entrants to find a foothold in these value chains.

In many mineral supply chains, the concentration of production is often underpinned by network efforts, lower costs, and, in my cases, by relatively energy- and emissions-intensive processes. Emerging or less-established producers struggle with higher capital and operating costs, including for energy, labour and transport. While these projects often tend to rate more highly on various environmental, social and governance (ESG) indicators, these efforts are not always adequately rewarded in the marketplace. As a result, many of these producers struggle to remain competitive in the global market.

Projects in geographically diverse regions often face difficulties to secure capital to advance, as they face higher upfront capital costs. Initial capital expenditures for mining and refining in regions outside the dominant player are on average 1.5 times higher than those within the top producing country.

The sharp declines in mineral prices in recent years have undermined the commercial viability of many projects in more diversified regions. Producers outside the dominant markets often face higher all-in sustaining costs, making it difficult to remain profitable during commodity downturns. As a result, several operations have been suspended or been placed under care and maintenance. These cost pressures, combined with ongoing price volatility and economic uncertainty, have constrained the growth of alternative supply sources.

In response, policy makers and markets are increasingly focused on exploring mechanisms to incentivise the development of diversified mineral supply sources. These interventions can take several forms, including public financial support through loans, subsidies and grants, aimed at reducing investment risks. However, there is growing recognition that financing support, on its own, may not be sufficient to accelerate the development of resilient and sustainable mineral supply chains. There is a need to consider more structured mechanisms that address underlying market risks, focusing on key price and demand uncertainties.

Rule-based market mechanisms can reduce price and volume risks, supporting long-term investment in diversified regions

While public financial support is essential to unlock near-term investment, particularly for early-stage or high-risk projects, it may fail to build a lasting market for more diversified supply chains. In highly concentrated markets, new entrants are subject to potentially extreme and unpredictable risks, including market manipulation by the incumbents. As a result, attention is increasingly turning to mechanisms, including standards-based commercial incentives and demand-side structures, that can mitigate some of the key price and volume uncertainties.

Unlike direct financial interventions, market-based mechanisms aim to reshape how minerals are priced, traded and procured. Certification schemes, for example, can enable product differentiation based on environmental, social and governance indicators, allowing responsible producers to access price premiums or preferred procurement status. Rather than directly injecting capital, these tools can support long-term economic viability for minerals projects aligned with diversification and performance goals.

These mechanisms aim to be more self-sustaining than direct public support. By creating demand for certified or price-stabilised minerals, they have the potential to incentivise commercial investment without necessarily requiring ongoing public financing support. Unlike project-specific and time-limited public interventions, market-based structures tend to be rules-based and scalable, offering greater predictability and policy stability across jurisdictions.

Price stabilisation mechanisms

Options that are generating increased interest are price stabilisation mechanisms. For example, in a response to the US Department of Energy's Request for Information, mine developers and mineral off-takers supported offtake pricing support such as contracts for differences (CfDs) and price floors.

CfDs and cap-and-floor models can help stabilise costs for both mineral producers and off-takers. In this model, a government or another intermediary sets a reference price for a mineral and commits to compensating producers if the market price falls below this level. Conversely, if market prices exceed the agreed reference price, producers return the excess to the government or intermediary. Although more complex than price floors alone, these instruments have the potential to prevent price distortions while reducing the likelihood of uncapped payouts by governments.

These models have already been widely used in markets for renewable capacity and other energy infrastructure to de-risk investment in new capacity, and similar principles could be applied to critical minerals to support supply growth without exposing investors to extreme price fluctuations. By providing a guaranteed revenue stream, CfDs and cap-and-floor models can facilitate long-term planning and mobilise private investment in new mining and refining projects.

A key challenge is determining the appropriate reference price that incentivises efficiency and cost-competitiveness while providing the investment signals to drive supply. Unlike the electricity sector, where CfDs have been used to support the deployment of renewables in a relatively open and competitive market, many mineral markets are concentrated and opaque. Pricing for several critical minerals relies on bilateral contracts and price reporting agencies rather than liquid exchanges, which may make it difficult to establish credible and efficient reference prices. Poorly calibrated benchmarks could unintentionally entrench incumbent advantages or distort investment signals. Nevertheless, if carefully designed, price stabilisation mechanisms could play an important role in reducing investment barriers and accelerating diversification.

Volume guarantee mechanisms

In addition to price stability, another critical factor in securing long-term investment is volume guarantees that provide a degree of demand predictability. Given the capital-intensive nature of mining and refining projects, developers require sufficient confidence that there will be sustained demand for their output over the lifetime of a project. Strategic procurement commitments and government-backed purchasing mechanisms can serve as guard rails by guaranteeing a minimum level of demand. These mechanisms mitigate the risk of market downturns or sudden demand shifts that could undermine the viability of new projects.

Governments can also influence market structures through standards-based market access policies. These policies ensure that only minerals that meet specific production or sustainability standards qualify for trade incentives or public procurement.

Demand aggregation, or co-ordinated purchasing, of critical minerals has also been explored as a potential solution to demand uncertainty. Although such mechanisms have been deployed in energy commodity markets, applying them to critical minerals can be complex due to the wide variation in product types and quality criteria. If managed effectively, collective procurement mechanisms could help stabilise supply chains and prevent supply shocks. However, given the potential complexities involved in governance, they require careful design and sufficient consultation with material consumers to ensure that they are useful to domestic end users.

Broader policy considerations

Despite the potential benefits of all these mechanisms, their introduction needs to be carefully managed. One of the primary difficulties lies in ensuring that price stabilisation and volume security mechanisms do not lead to excessive market distortions. CfDs and cap-and-floor models, while effective in smoothing out price volatility, risk weakening the incentive for producers to improve efficiency or innovate to reduce production costs. If structured poorly, they may encourage dependence on state support rather than fostering a competitive, self-sustaining market. Similarly, long-term offtake agreements, while providing much-needed certainty for developers, could entrench supply relationships that become inefficient or uncompetitive over time, locking in production structures that fail to adapt to changing market conditions.

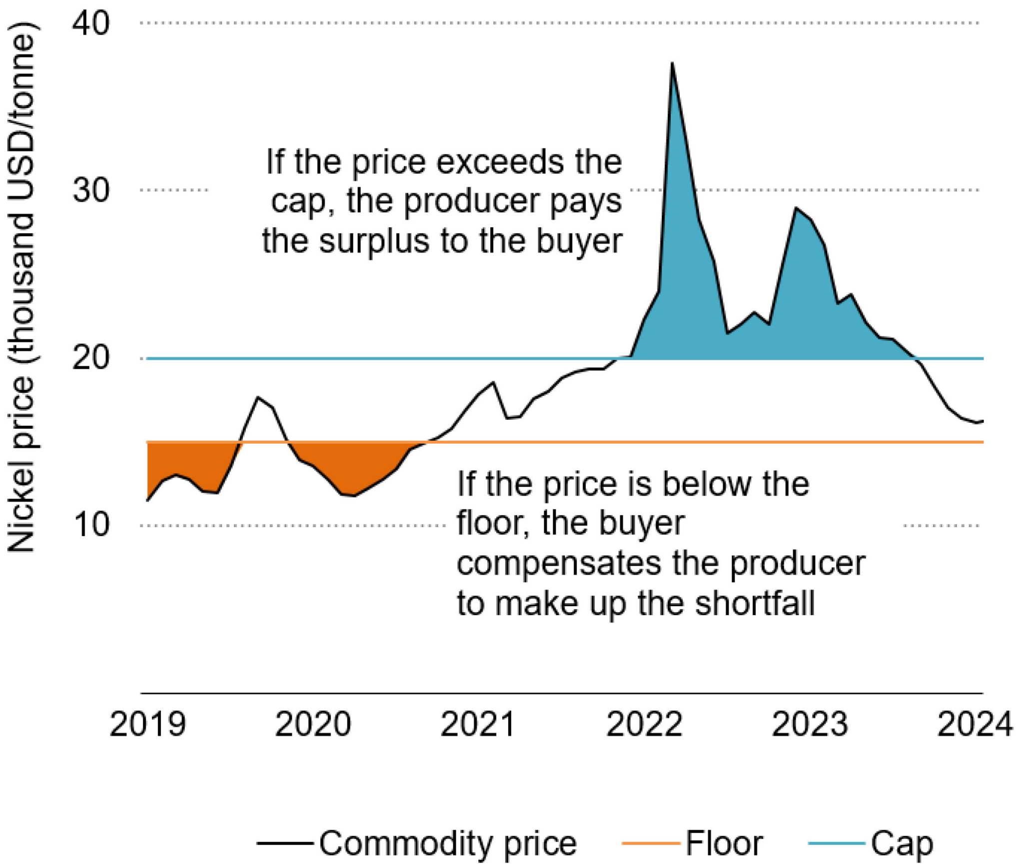
In contrast to financial support mechanisms, where negotiations happen bilaterally between governments, financing institutions and producers, introducing support for rule-based market mechanisms will require significant co-ordination and regulatory alignment to be properly designed and implemented. Although they may still need transitional public support to catalyse early adoption, they are intended to support a sustainable market structure. Mitigation of mineral price risks has the potential to crowd in private investment, but policy makers must strike a delicate balance in providing enough certainty to unlock investment while allowing competitive forces to drive innovation and sustainable supply growth.

Effective differentiation of commodity products along production standard and origin criteria requires clear, agreed-upon standards and traceability measures. Many jurisdictions are already introducing regulations which directly or indirectly require specific origin and ESG data. For these systems to be effective, they must be carefully designed and implemented, addressing key technological and economic challenges.

Well-designed market-based mechanisms can support production in diversified regions

Nickel market case study: Fiscal impacts of cap-and-floor mechanisms

Illustrative cap-and-floor mechanism



Sensitivity analysis of government cost/revenue
(annual average between 2019-2024 in billion USD)

Floor price (thousand USD/tonne) \ Cap price (thousand USD/tonne)	15	17	18	20	22	25	28
10	1.6	1.0	0.7	0.3	0.0	0.0	0.0
12	1.6	1.0	0.7	0.3	0.0	0.0	0.0
15	1.6	0.9	0.7	0.3	0.0	-0.0	-0.0
17		0.9	0.7	0.3	-0.0	-0.0	-0.0
18			0.5	0.1	-0.2	-0.2	-0.2
20				-0.1	-0.4	-0.5	-0.5
22					-0.7	-0.8	-0.8

Note: The values shown in the right-hand chart represent the annual average government revenue or cost associated with the total production volume of nickel producers outside the top three producers (Indonesia, China and Russia) over the 2019-2024 period.

Mechanisms to support mineral production should balance supply security objectives with competitive signals that incentivise efficiency

A sensitivity analysis on the potential costs and benefits of implementing a cap-and-floor model in the nickel market highlights the challenges involved in introducing market-based mechanisms. The analysis represents a range of cap-and-floor prices, applied to nickel production outside the top three producer countries (without production cost or emissions or energy intensity differentiation).

The left-hand chart illustrates how a cap-and-floor mechanism would have operated in the nickel market over recent years. When market prices fell below the floor price, the mechanism would have triggered government compensation to producers to ensure a minimum revenue level. Conversely, during price spikes in 2022 and 2023, when prices greatly exceeded the cap, producers would have returned a portion of their windfall gains to the government.

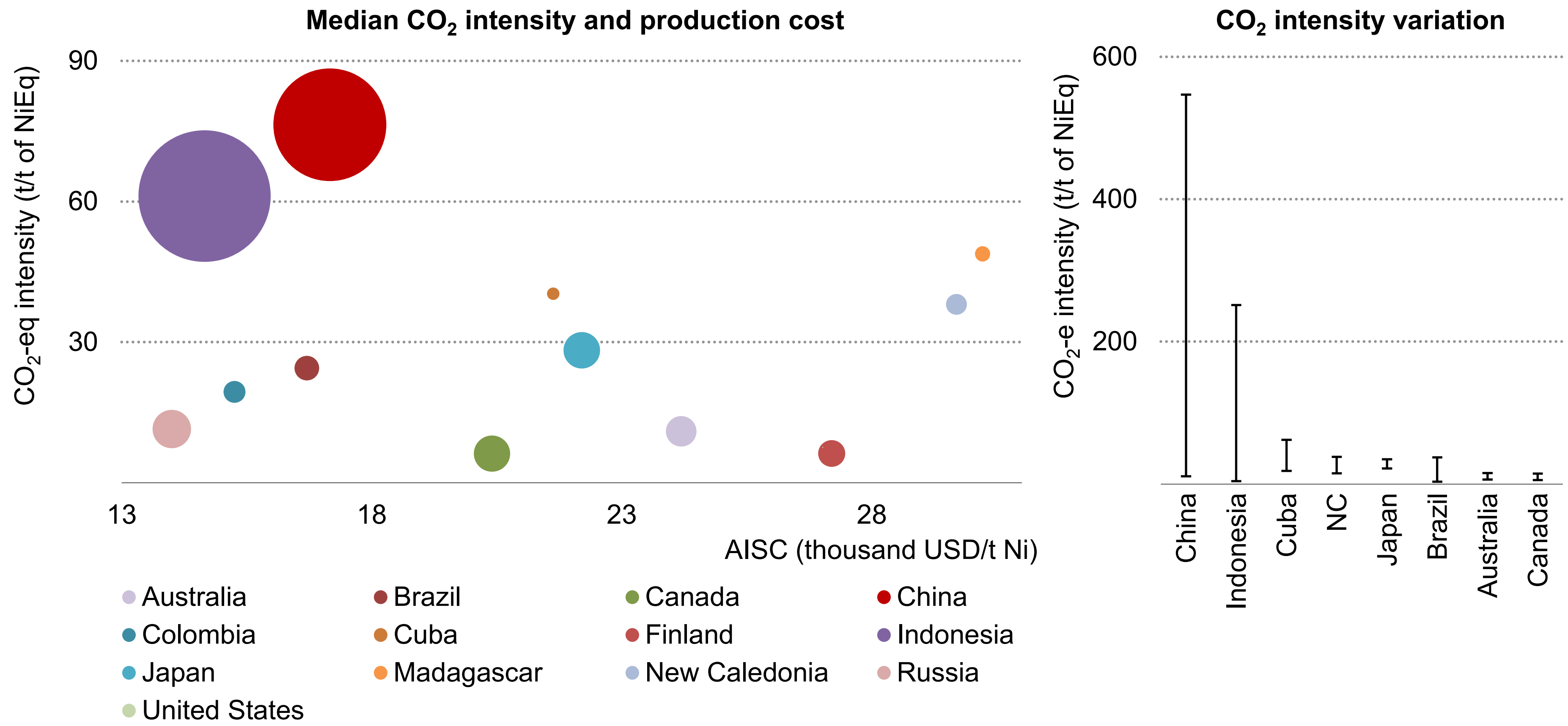
The right-hand chart provides a sensitivity analysis of the fiscal implications of different cap-and-floor combinations, showing the potential government cost or revenue based on historical price movements. The results reflect the trade-off between producer support and fiscal sustainability. For example, a low floor and low cap scenario would generate significant government revenue, while a high floor and low cap would result in a net outflow.

This analysis underscores the importance of calibrating reference prices carefully. Setting the floor too high may provide strong investment incentives but result in unsustainable fiscal burdens. Conversely, overly conservative pricing may limit the effectiveness of the instrument in catalysing new supply.

Additionally, the analysis assumes uniform treatment of all producers, regardless of their cost structures, which may lead to inefficient outcomes in practice. Lower-cost producers may receive windfall benefits at government expense, while higher-cost but strategically important projects may still struggle to secure financing if the floor price is not sufficiently supportive.

This means that determining appropriate reference prices for cap-and-floor mechanisms would likely require a combination of historical market data, forward prices and negotiated benchmarks with industry stakeholders. Such an approach can help ensure that the mechanism reflects both market realities and the strategic objectives of mineral supply diversification. Incorporating input from producers, off-takers and financial institutions can enhance the credibility and effectiveness of the scheme while aligning incentives across the value chain.

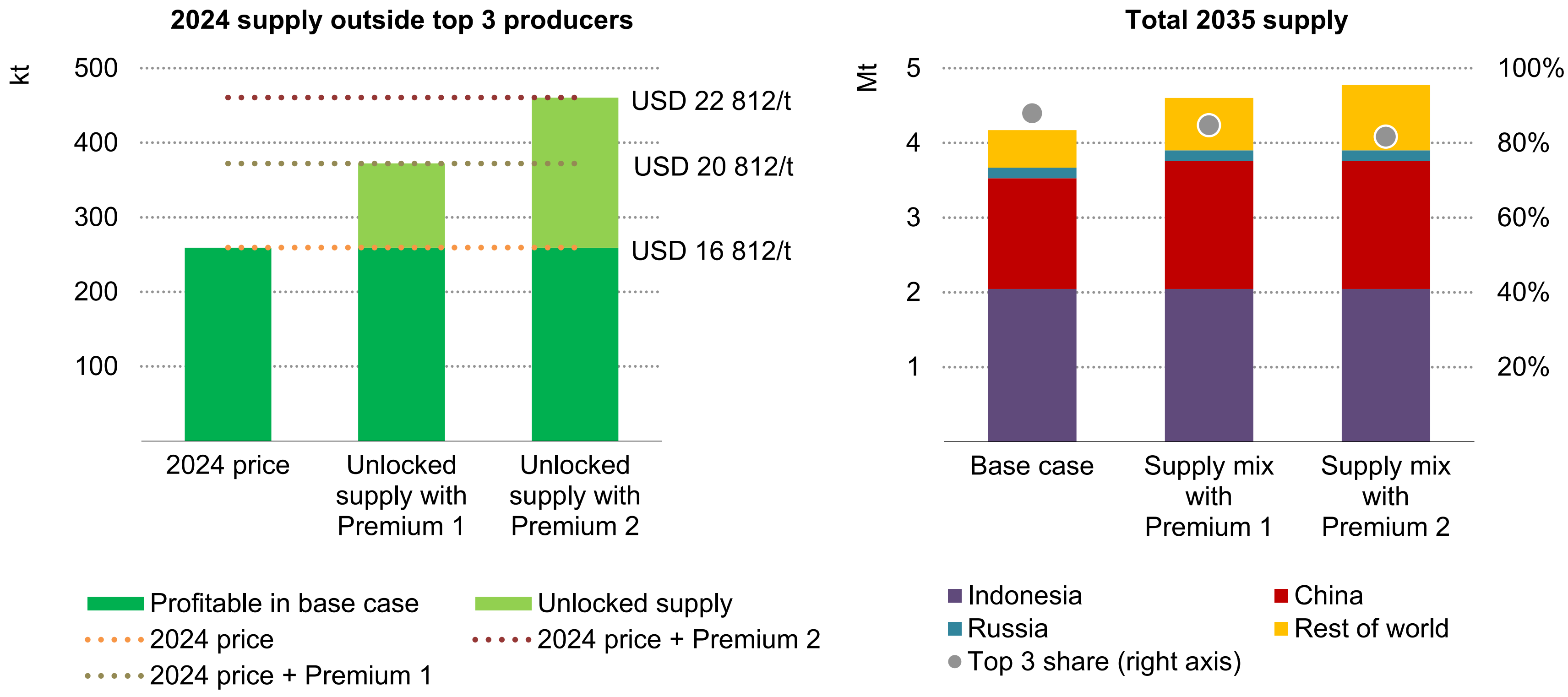
Market dominance in nickel refining is often linked to low costs enabled by energy- and emissions-intensive production processes



Notes: Size of the bubble is proportionate to the country's production level. AISC = average all-in-sustaining costs across operations in 2024; NC = New Caledonia. CO_2 intensity includes all GHG emissions for the saleable nickel product, including scope 1 & 2, freight and downstream processing.
Source: IEA analysis based on Skarn Associates and Project Blue.

Incentives for cleaner nickel could unlock almost double the supply from outside today's dominant producers in 2024; this could reduce concentration by 7% in 2035

Level of nickel supply under the base case and with supply unlocked through incentives for cleaner nickel



Notes: "Cleaner" nickel is nickel from operations with a CO_2 intensity of lower than 20 CO_2-eq per tonne of output. Incentive 1 = USD 4 000/tonne; Incentive 2 = USD 6 000/tonne. Analysis uses weighted all-in-sustaining costs compared with 2024 nickel price and the 2024 nickel price plus the selected incentive. 2035 production in the rest of world considers reopened and restarted projects from IEA's high production case and beyond. Production covers 69% of supply in 2024 and 88% in 2035.

Sources: IEA analysis based on Skarn Associates (CO_2 intensity) and Project Blue (cost).

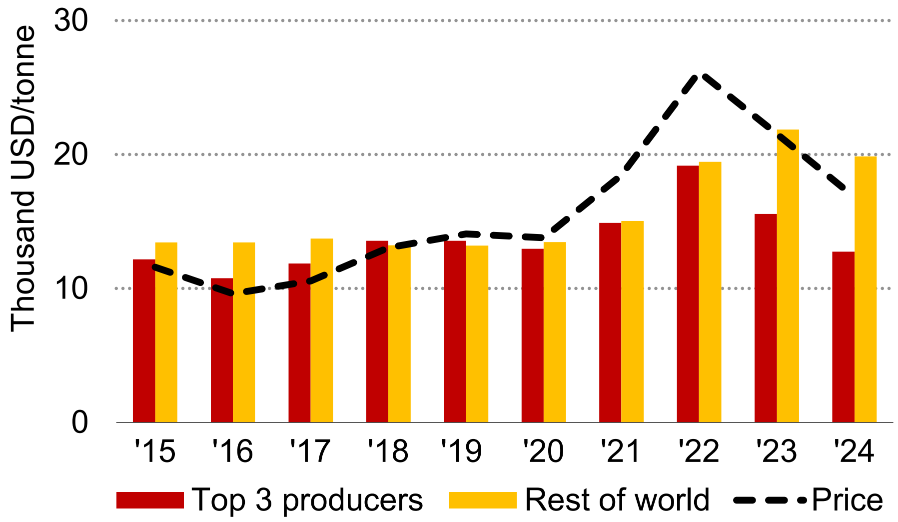
Standards-based market access alongside price and volume security has the potential to enable supply diversification and security

Although the implication of different pricing mechanisms will vary by mineral, the nickel market can provide an interesting case study as low nickel prices spurred by high-emissions, low-cost nickel have led many market participants to discuss the potential for a "green premium". Over the past ten years, the nickel market has become increasingly concentrated, with the top three producers taking their market share from just over 50% in 2015 to almost 80% in 2024, which is expected to continue growing moving forward (see Chapter 2, "Outlook for nickel").

Nickel operations outside the top three producers have had all-in-sustaining costs that are almost 15% higher than those seen in the top three suppliers. Production in these areas is therefore particularly sensitive to price volatility, with 80% of ex-top three producers' production costs in 2024 estimated to stay above the prevailing price in 2024, thus not profitable. If prices remain at the low end of the commodity cycle, this gap could widen dramatically and could impact almost all of the output in non-dominant players by 2030.

While some production volumes within the top three players face similar challenges, much of the world's low-cost nickel production is concentrated in China and Indonesia. Production in these countries is typically more emissions-intensive due to fossil fuel-heavy power mixes and reliance on energy-intensive processes like rotary kiln electric furnaces. Although other processing methods, such as high-pressure acid leaching, which converts low-grade laterite ores to higher-purity nickel, are less energy- and emissions-intensive, these still make up a small share of production. However, the best performers in the non-dominant producers have CO_2 intensities that are less than 5% that of the worst performer.

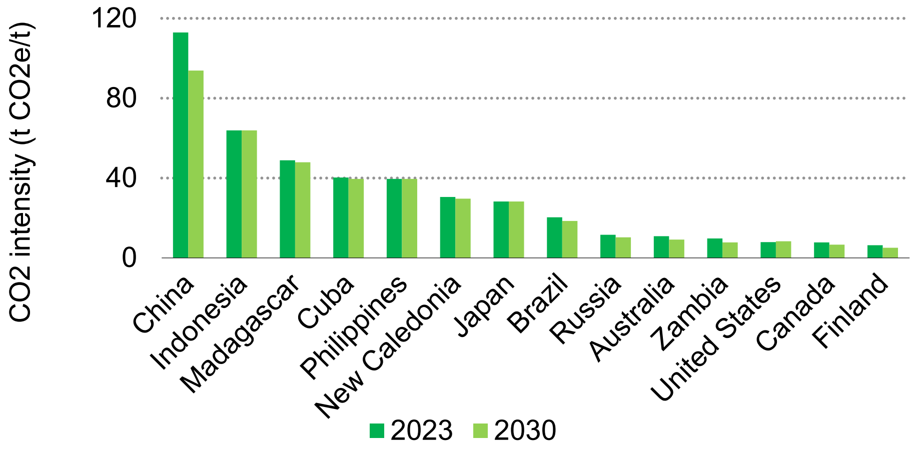
Nickel production all-in-sustaining cost and price



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

Looking towards the future reveals marginal improvements in emissions intensity across countries, with average CO_2 intensities falling by 7% across countries from 2023 to 2030. This is largely driven by China, which sees a 17% decline as the country's power mix decarbonises. Countries outside the top three producers also see declines, including Australia, Canada and Brazil; however, these countries already have some of the lowest CO_2 intensities in the market.

Average CO_2 intensity of nickel production in selected countries



Note: NC = New Caledonia
Source: IEA analysis based on Skarn Associates.

These concerns have led market participants to call for some form of incentives to favour products with lower emissions intensities, which could work to support operations during periods of price volatility, incentivise the greening of nickel production and allow for more diversification. Although some market players have signalled that they take performance into account when sourcing nickel, many market participants have noted that they have so far not seen any meaningful premium emerging on the market for "clean" products. While some studies have shown a connection between ESG performance and market performance, this has yet to materialise in the market.

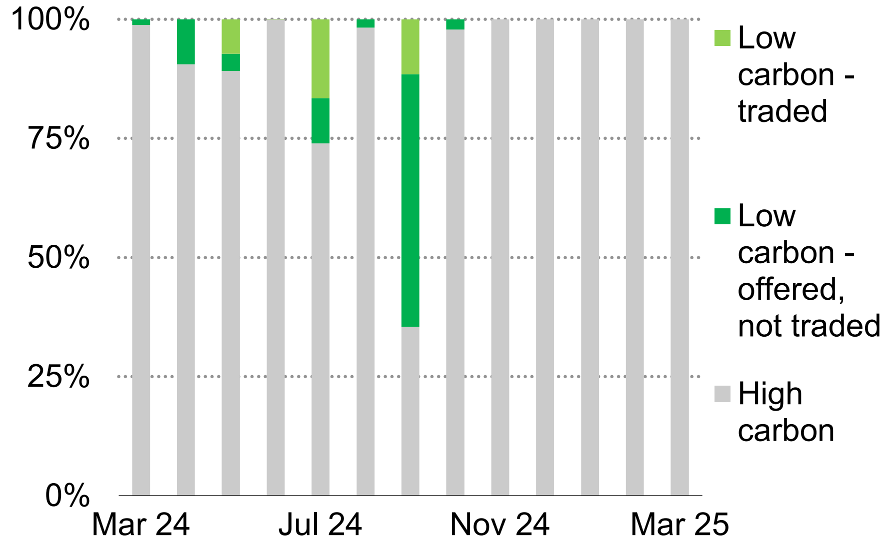
In response to conversations around a "green premium", in March 2024 the LME rejected calls to create a differentiated trading platform, noting that the market is not yet large enough to support vibrant trading in a dedicated green futures contract. However, the trading platform did partner with Metalshub to introduce a price reporting mechanism on Class 1 nickel traded, with the ability for buyers to access product carbon footprint and ESG credential information uploaded by sellers. Buyers can then use this to make purchasing decisions. Based on this, Metalshub reports the amount of "green" Class 1 nickel offered and traded, which is defined as having a registered carbon footprint lower than 20 tonnes of CO_2-equivalent per tonne of output.

As of February 2025, a total of 1.4 Mt of "green" nickel was offered on the LME platform, 7% of the total amount offered, although only almost 50% of that "green" nickel was traded. Once the index has a sufficient amount of transactions, Metalshub plans to publish a Nickel Class 1 Premium Index, which may give insights into market participants' willingness to pay a premium to access "green" nickel.

A key question in the "green premium" discussion is how much diversification a nickel price premium could support. Using an illustrative benchmark of 20 tonnes of CO_2-equivalent per tonne of output, as utilised by the LME, "green" nickel supply from outside today's dominant producers accounts for just below 15% of global production. Approximately half of this production is at risk at 2024 prices, meaning that a "green" premium could allow further supply to be unlocked. Considering a "green" premium of USD 4 000/tonne of output, almost 50% more supply could be unlocked outside of the top three producers. If the premium is raised to USD 6 000/tonne, bringing the price nearly to the average level seen during the high period of 2021 to 2023, this raises to almost 80% more supply.

In the base case supply scenario, the share of top three producers increases from 78% today to 83% by 2035 as Indonesia and China continue to raise outputs. A "green" premium set at USD 4 000/tonne could unlock 40% more supply outside the dominant producers, assuming that projects which have gone under care and maintenance, halted, or closed during the low-price environment of the last year come back online with the price support. Increasing the premium to USD 6 000/tonne means that 25% more supply is unlocked, lowering the top three producers' share to around 80%. This could be even higher if a "green'" premium allows other projects which are currently in early stages of development to come online.

Volume of low- and high-carbon nickel offered and traded on Metalshub



Source: IEA analysis based on Metalshub.

Although these premium levels are provided merely as an illustration of potential impact, any effectively designed "green premium" or other ways to incentivise cleaner nickel should be responsive to current market considerations. This could work to improve diversification in the nickel supply chain, provided it is designed in a way that ensures de-risking without undermining long-term competitiveness and efficiencies.

In April 2025, the LME announced that it has started to explore the potential for a price discovery mechanism for sustainable metal premia for a wider range of metals, including LME-approved aluminium, copper, nickel and zinc, following continued stakeholder interest. This would involve establishing a pricing administrator, who would set the rules, policies and process for the sustainability premia, including incorporating a more comprehensive set of criteria than carbon footprint.

A "qualification" approach for cleaner and more responsible nickel is also being discussed. This involves setting defined ESG criteria that producers must meet to access specific market segments, such as strategic reserves or government procurement channels. Rather than pricing alone determining market participation, this model introduces performance-based standards as a market access condition. By linking preferential access to ESG performance, this approach incentivises producers to adopt stronger environmental and social practices while supporting diversification goals. However, its effectiveness depends on broad stakeholder consensus around the ESG criteria used, as well as transparent and credible verification mechanisms to ensure compliance.

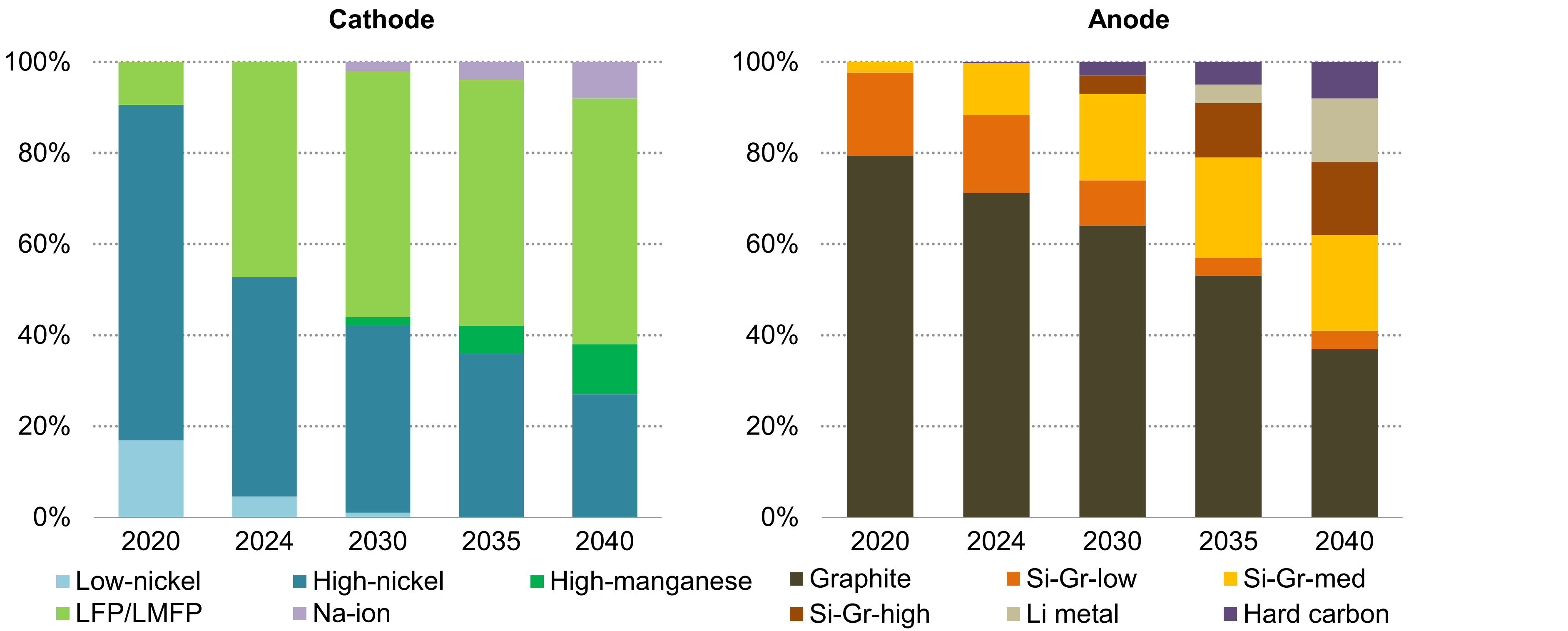
Although discussions on incentives for sustainable nickel have thus far focused on the emissions intensity of production, any market mechanism which aims to incentivise higher production standards needs a more holistic definition of sustainability, including land and water pollution, biodiversity, human rights and governance abuses.

In addition, any standards criteria that are established must be reliable and transparent, with robust and credible methodologies for assessing performance and transmitting data along the supply chain. All these factors need to be taken into account when looking to incentivise the implementation of responsible production standards.

Beyond NMC batteries: Supply chain issues for emerging battery technologies

LFP cathodes are set to capture a growing share of the EV battery market, while manganese-rich chemistries, sodium-ion and lithium metal chemistries emerge

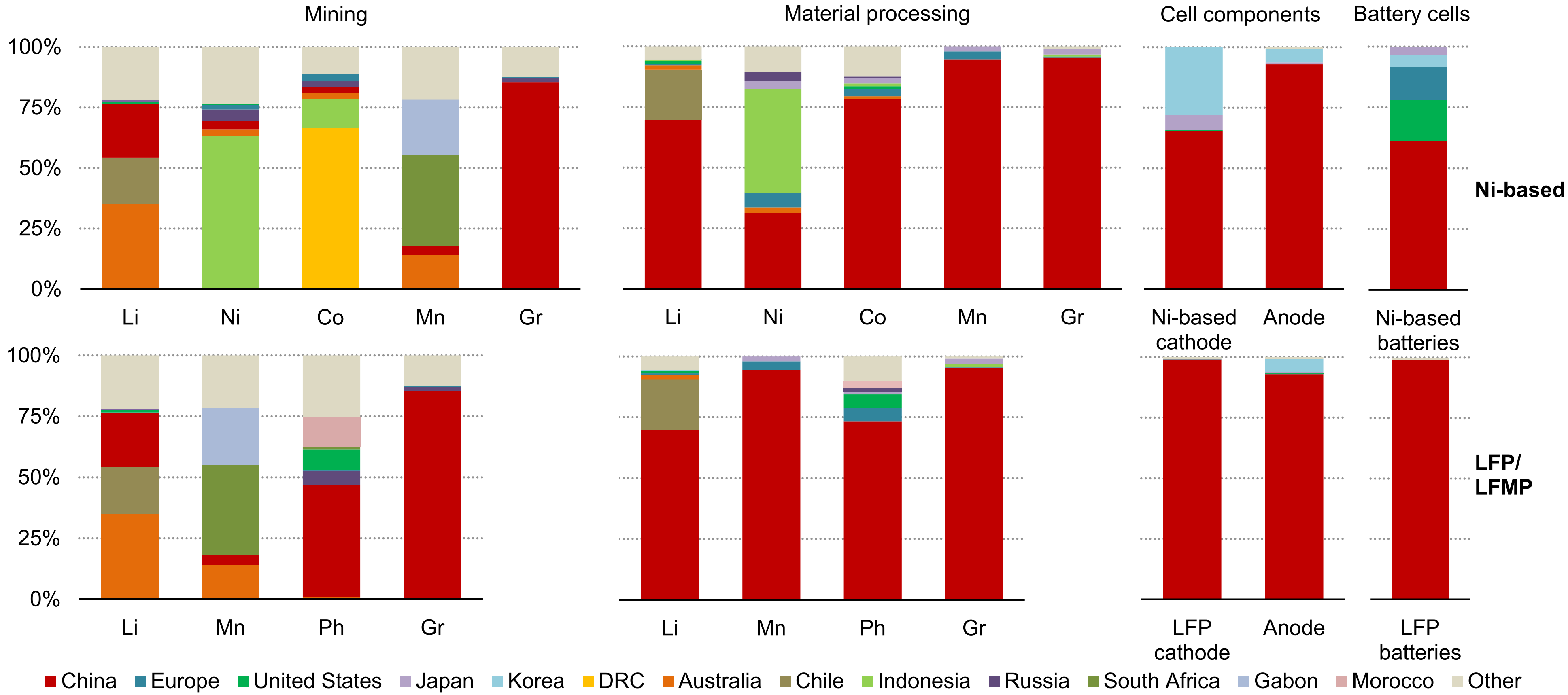
Electric car battery chemistry projections in the base case



Notes: LFP = lithium iron phosphate; EV = electric vehicle; LMFP = lithium manganese iron phosphate; Na-ion = sodium-ion. Low-nickel includes: NMC333 and NMC532 (NMC = lithium nickel manganese cobalt oxide). High-nickel includes: NMC622, NMC721, NMC811, lithium nickel cobalt aluminium oxide (NCA), lithium nickel manganese cobalt aluminium oxide (NMCA), lithium nickel oxide (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 LFP battery supply chain is even more dominated by China than conventional nickel-based chemistry supply chains

Geographical distribution of the LFP and nickel-based lithium-ion battery supply chain, 2024

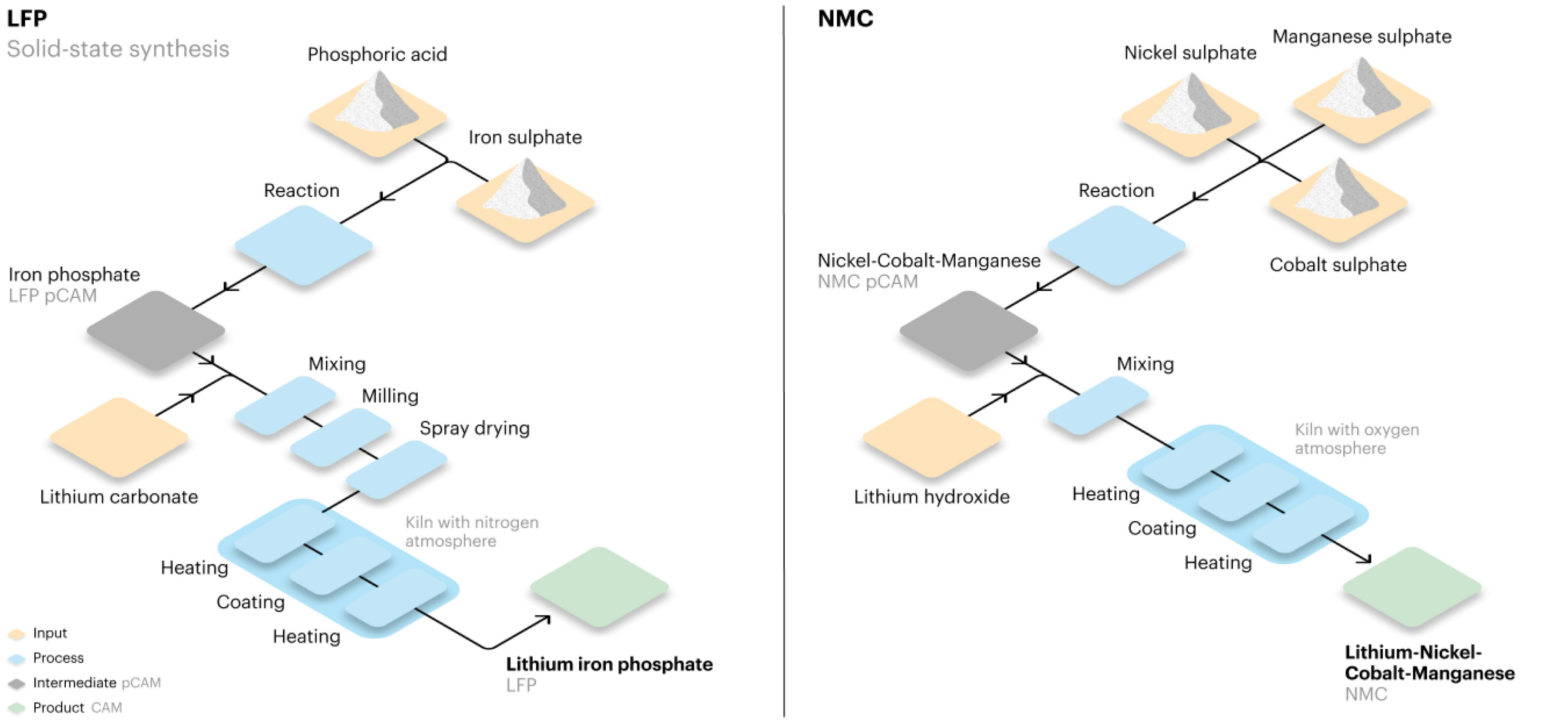


Notes: Ni-based = nickel-based cathodes. Li = lithium; Ni = nickel; Co = cobalt; Gr = graphite, Mn = manganese, Ph = phosphate; Material Processing: Mn = battery-grade Mn sulphate, Ph = battery-grade phosphoric acid, Gr = battery-grade graphite. DRC = Democratic Republic of the Congo.

Sources: IEA analysis based on USGS (2025), Mineral commodity summaries, BloombergNEF and Benchmark Mineral Intelligence.

The LFP and NMC cathode material production process

LFP and nickel-based cathode active materials production processes



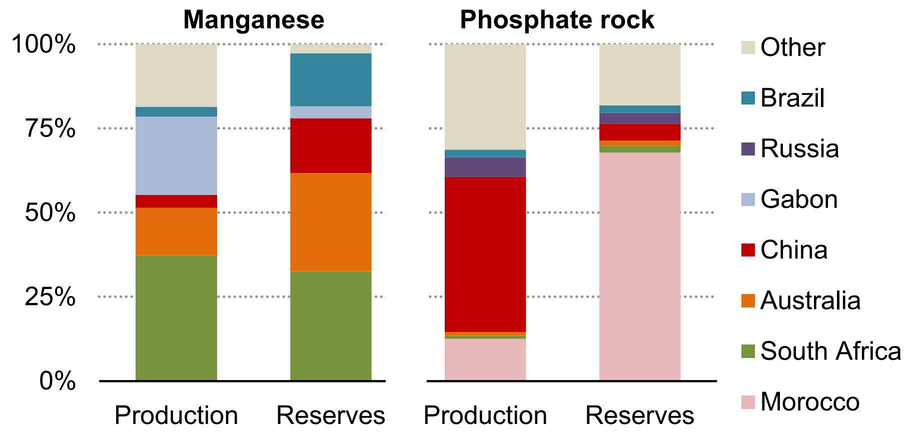
Notes: LFP = lithium iron phosphate; NMC = lithium nickel manganese cobalt oxide; pCAM = precursor cathode active material; CAM = cathode active material. NMC cathode production process is based on a nickel-rich NMC such as NMC811.

Mapping the supply chain for LFP and emerging battery technologies such as sodium-ion and solid-state batteries

In 2020, nickel-based lithium-ion batteries, predominantly lithium nickel manganese cobalt oxide (NMC) batteries, supplied over 90% of the global electric car battery market, while lithium iron phosphate (LFP) batteries comprised less than 10%. However, by 2024 almost half the global electric car battery market was supplied by LFP batteries, with this exceptional resurgence displacing nickel-based chemistries. Initially driven by high nickel and cobalt prices in 2021-2022, continued growth in LFP deployment sustained even as mineral prices fell, driven by innovations improving the energy density of LFP and increased price competition in the EV market.

The same period has also seen the emergence of sodium-ion batteries, the only commercial EV battery chemistry that does not contain lithium. There is also a trend towards greater use of manganese in lithium-ion cathode chemistries, through LFP variants such as lithium manganese iron phosphate (LMFP), or manganese-rich nickel-based chemistries. Finally, there is the anticipation of solid-state batteries, which provide yet another major shift in chemistry and supply chains. For many years, much attention has understandably been given to minerals such as nickel and cobalt, which are essential for nickel-based lithium-ion batteries such as NMC. However, the rapidly evolving space of battery technologies and chemistries which depend on different critical minerals from the conventional nickel-based chemistries is bringing new battery supply chains into focus. LFP, the new leading chemistry, is a case in point.

Manganese and phosphate rock mining and reserves, 2024



Source: IEA analysis based on USGS (2025), Mineral commodity summaries.

Mining

In the upstream, the LFP and LMFP supply chain differs from nickel-based chemistries by requiring no nickel and cobalt but instead relying on phosphate (and manganese for LMFP) supply chains. Phosphate rock is predominantly mined for the production of phosphoric acid in the fertiliser industry, but has other uses in the food and beverage industry and industrials. LFP batteries require food-grade purified phosphoric acid (PPA) with minimal impurity elements often derived from high-quality phosphate concentrates. In terms of mining, phosphate rock supply is less concentrated than cobalt and nickel. Global mined phosphate is led by the People's Republic of China (hereafter, "China"), which produces 45% of global mined supply, followed by Morocco, supplying almost 15%, and the United States with almost 10%.

Despite China's leading role in production, Morocco holds by far the largest reserves of phosphate rock with almost 70% of global reserves, while China holds just 5%. Over recent years there has been a flood of Chinese battery investment into Morocco to secure supplies of phosphate for LFP battery production. Morocco also has free trade agreements with the European Union and the United States, enabling greater potential access from Chinese LFP producers to these markets. Production of battery-grade PPA is most suited to specific forms of phosphate rock, which comes in two primary types: sedimentary and igneous. Igneous deposits are the ideal form required for LFP batteries as they contain high-quality phosphates with minimal heavy metal impurities, being more economical to produce battery-grade PPA. However, only around 10% of the world's phosphate deposits are igneous. Brazil, Canada, Finland, the Russian Federation (hereafter, "Russia") and South Africa hold the leading deposits of igneous phosphate rock. Despite this, phosphate rock supply is unlikely to be a constraint on LFP production in the near and medium term as sedimentary sources can also be used for LFP production. Most of the sources being used by China, the current top phosphate rock miner and LFP producer, are sedimentary sources.

Conventional LFP chemistries contain no manganese, but the emergence of LMFP and its continued growth mean that manganese is a mineral of growing importance for its supply chains. Manganese also remains a critical component for stabilisation for almost all nickel-based chemistries. Mined manganese is more diversified in supply than nickel or cobalt, with South Africa being the top supplier with 40% of production, followed by Gabon with almost a quarter and Australia with 15%. Mined manganese is less of a constraint compared with other battery metals due to its relative abundance.

Refining

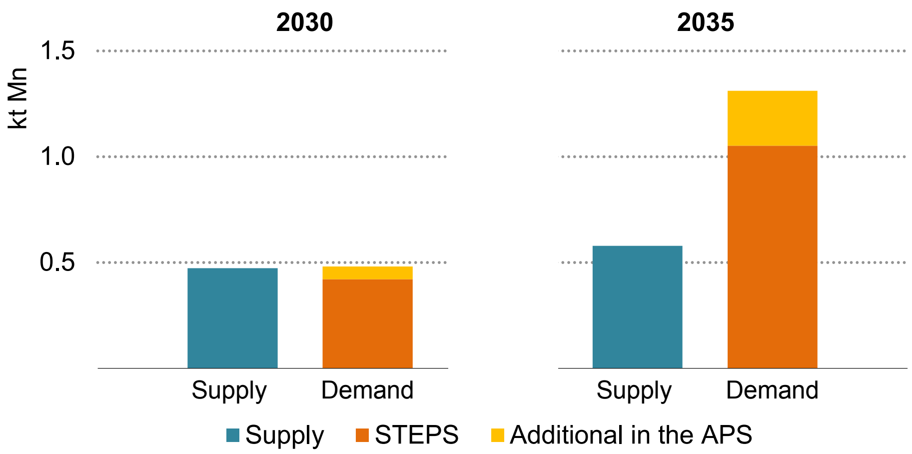
The refining of phosphate rock is a significant issue for the supply chains of LFP and LMFP battery chemistries, while the refining of manganese is critical for nickel-based and LMFP battery chemistries going forwards. Production of battery-grade PPA is a particular potential bottleneck for LFP. China currently dominates battery-grade PPA supply with almost three-quarters of global production, followed by the United States with just over 5% and Europe with 5%, with Belgium supplying two-thirds of this. Despite holding the largest reserves and being the second-largest phosphate rock miner, Morocco currently supplies just 3% of global battery-grade PPA.

Current major players in PPA production include Wengfu Group, Yuntianhua, Xingfa and Chengxing.

Some sources anticipate that a PPA supply deficit could develop as early as 2030 as the rapid increase in LFP battery demand outpaces the development of PPA refining capacity. Morocco is set to have the greatest growth in ex-China PPA supply, with expansions being driven by the state mining company OCP Group. Based on the pipeline, Morocco and the United States are likely to be the largest sources of PPA supply outside of China by 2030, together accounting for almost 40% of supply in 2030. Development of PPA production capacity outside of China faces cost-competitivity challenges stemming from the economies of scale and established phosphate production advantages in China. There are also additional challenges related to waste and by-product disposal.

The production of battery-grade manganese sulphate is another source of concern for both nickel-based and LMFP supply chains. China dominates the supply of high-purity manganese sulphate with 95% of global production in 2024. There are only two refineries outside China, in Belgium and Japan. Current major players in manganese sulphate production include Guizhou Dalong Huicheng New Material, ISKY Chemicals and Guizhou Red Star Development. Most battery-grade manganese sulphate projects announced and under development are in China. There are only a few projects planned outside of China, and they face significant capital and operating cost challenges compared with China from reduced economies of scale, limited production expertise, and stricter environmental requirements to handle by-products and waste.

Battery-grade manganese sulphate supply and demand



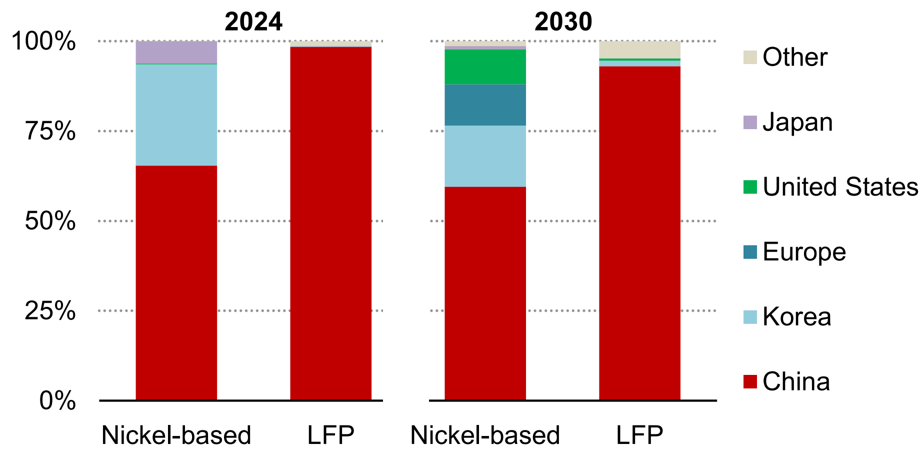
Notes: kt = kilotonnes; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Supply refers to total capacity for battery-grade manganese sulphate including recycling capacity
Source: IEA analysis based on BloombergNEF (2024).

Based on announced capacities for battery-grade manganese sulphate, including recycling, there appears to be sufficient supply for demand in both the STEPS and APS in 2030. However, the project pipeline suggests that a major supply deficit could develop for battery-grade manganese sulphate in the early 2030s. By 2035, anticipated supply would cover only 55% of demand in the STEPS and 45% in the APS. Unless there is significant additional supply development, manganese refining may provide a major bottleneck, particularly for nickel-based chemistry production, as well as hindering production of LMFP. For LMFP, some producers in China are also using manganese tetraoxide, manganese dioxide and other high-purity manganese sources instead of sulphate, which could mitigate some impacts on LMFP production, but manganese sulphate is required for nickel-based chemistries. Both battery chemistry groups depend on the same graphite supply chains for the anode material, which is dominated by China with 95% of global production.

Cathode material

There are two broad stages to nickel-rich NMC production (the leading nickel-based cathodes). First, production of the hydroxide precursor cathode material (pCAM), followed by solid-state synthesis of the final NMC cathode material. The pCAM stage involves reacting the nickel, cobalt and manganese sulphate precursors to form the nickel manganese cobalt hydroxide pCAM material. Lithium hydroxide is then mixed with the pCAM and heated in a furnace at almost 1 000 °C, often under a pure oxygen atmosphere, to form the final NMC cathode material. LFP cathode production also has two broad stages and is predominantly produced industrially in a thermal process. The iron phosphate pCAM is produced first through reacting the high-purity PPA with iron compounds. After this the iron phosphate pCAM is mixed and ground with lithium carbonate (lithium hydroxide can also be used), and a carbon source before heating in an oxygen-free atmosphere over 500 °C (typically under pure nitrogen) to produce the LFP material.

Geographical distribution of cathode production based on announced projects



Source: IEA analysis based on BloombergNEF (2024).

While China leads the production of both nickel-based and LFP cathodes, the LFP cathode supply is significantly more concentrated. The supply of nickel-based cathode material is led by China with almost two-thirds of global production capacity in 2024. Korea is the other major player, holding almost 30% of production capacity, while Japan holds a 5% share. In stark contrast, LFP cathode production is completely dominated by China with 98% of global production capacity in 2024. State subsidies and earlier favourable patent arrangements enabled China to dominate LFP production. These patents expired in 2022, enabling LFP to be produced and used internationally; however, the expertise and experience producing LFP at industrial scale remains in China.

Looking ahead, taking into account all cathode material projects under construction and announced, there are signs of diversification in the supply of nickel-based cathodes. Both Europe and the United States grow from a negligible share today to holding 10% each of global production capacity by 2030. LFP supply, however, appears set to remain dominated by China with almost 95% of future global production capacity in 2030, based on the current project pipeline.

At the battery cell production stage, LFP cells are again almost entirely produced in China, while nickel-based battery cell production is considerably more diversified with China supplying only 60% of the market in 2024; the United States and Europe are the other major production regions with around 30% of production together, and Japan and Korea combined produce around 10%.

Production equipment differences

The NMC and LFP production processes hold some broad similarities, but there are key differences in process and the equipment or machinery required. LFP requires more grinding due to its nanoparticle size for best performance, often requiring additional milling equipment. Moreover, LFP performance is highly dependent on particle coating, size and shape. As a result, LFP production processes use spray dryers to enhance uniform carbon coating and homogeneity of the nanoparticles. Each production process uses different gas sources during the furnace step, oxygen for nickel-rich NMC and nitrogen for LFP. At the battery cell production stage, there is very little difference between NMC and LFP in terms of production equipment, with some major Chinese players claiming to be able to switch cell production line between NMC and LFP in as little as a week. China's Wuxi LEAD Intelligent Equipment is the world-leading company for battery cell production machinery, though the majority of Japanese and Korean battery cell production machinery is produced within their countries.

Efforts to build diversified LFP battery supply chains need to pay growing attention to supply chain issues including raw materials and equipment

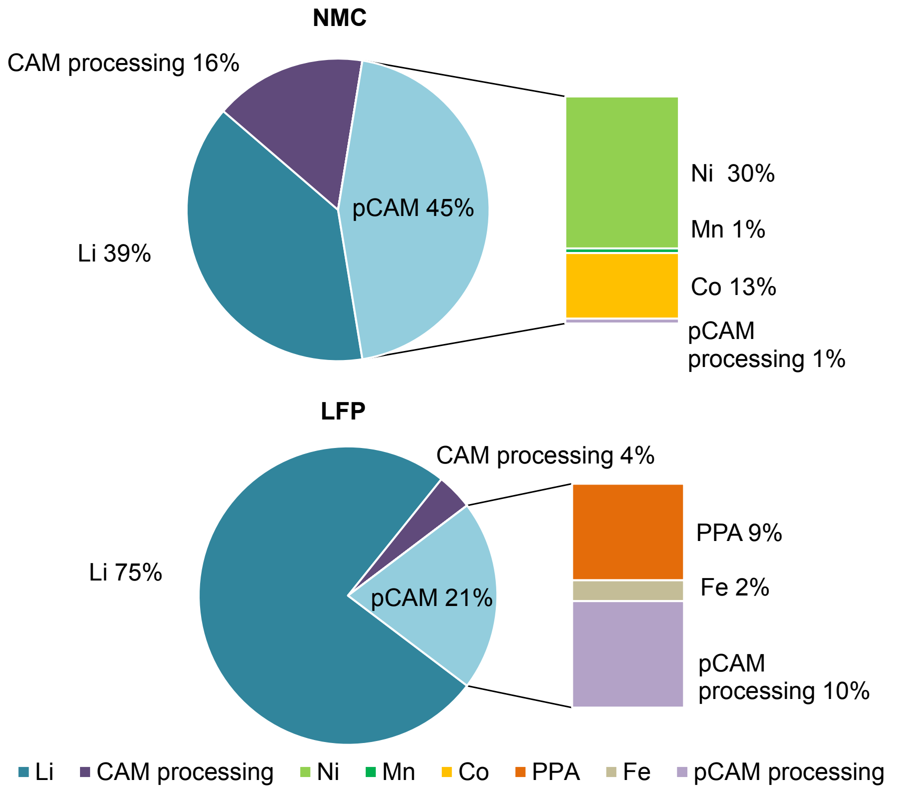
As LFP takes a larger market share, efforts to establish LFP battery manufacturing outside of China are gaining momentum, particularly in North America, Europe, Korea and Japan. However, there are considerable challenges to be overcome for these facilities to be competitive, such as securing reliable supplies of raw materials, achieving cost-competitiveness with established Chinese players, and accessing key technologies, equipment and machinery.

LFP production cost and supply chain integration

LFP prices from China are exceptionally low, which makes it very difficult for other players to compete. Chinese LFP producers benefit from its highly integrated supply chain. China is the dominant producer of lithium carbonate, battery-grade PPA, manganese sulphate and graphite anodes, but iron sulphate (common iron precursor for making iron phosphate pCAM for LFP) also has a unique position in China. Iron sulphate is a by-product of titanium dioxide production where China is the leading producer. As a result, key material inputs are available in China at very low cost, which is difficult to replicate in other parts of the world. China supplies 95% of high-purity manganese sulphate and 75% of battery-grade PPA, and securing these materials from alternative sources is currently challenging and often comes at a higher cost. These cost premiums will remain unless there are significant efforts to build diversified supply sources for these materials. Beyond the raw material advantages there is also significant LFP oversupply in China, with fierce competition further driving down prices.

The cost structure for LFP and NMC cathode material production in China shows that raw materials constitute the majority of total cathode material cost, around 85% for both NMC and LFP. This underscores the importance of securing material supplies in achieving cost-competitiveness in cathode production. Excluding lithium, other raw materials for NMC pCAM make up a significantly higher fraction of total cost than for LFP pCAM, with nickel, manganese and cobalt sulphate almost half the cathode cost, while LFP, PPA and iron are around 10% of the cost. Lithium carbonate makes up three-quarters of LFP cost in China, demonstrating the sensitivity to lithium prices. CAM processing costs for NMC are also significantly higher due to its increased production complexity and sensitivity. Outside of China, LFP processing costs would be considerably higher given higher costs for the pCAM material inputs coupled with more expensive equipment. Some regions also have higher energy costs, further limiting competitivity.

NMC and LFP cathode material production cost structure



Notes: PPA = battery-grade purified phosphoric acid; Fe = Iron. Costs in China. NMC is based on NMC622. Material input prices are the average prices from 2019-2024 for lithium carbonate for LFP, lithium hydroxide for NMC, and nickel sulphate, manganese sulphate and cobalt sulphate for NMC.

Equipment and machinery

Another critical area that China leads is battery cell and cathode material production equipment and machinery. There are many similarities between nickel-based and LFP cathode production equipment, and all this equipment can be produced outside of China, particularly in Japan and Korea. However, Chinese machines have three critical advantages: lower cost, increased production efficiency and scale, and shorter lead times. Key manufacturers in China include Dongguan Longly Machinery, Jiangsu Qianjin Furnace Industry Equipment and ALPA Powder equipment.

As a result, even though equipment and machinery for LFP production is available outside of China some players report that machines from China are half to one-third of the cost of those available outside of China. Some Chinese LFP cathode production machines also have superior. Some mills and spray dryers from China for LFP production operate at higher production efficiencies – potentially two to three times throughput – than those available outside China, enabling improved production economics. In addition, roller hearth kiln furnaces from China are much larger, enabling increased economies of scale and production volume. Finally, roller kiln furnaces ordered from outside China can take from 1-1.5 years to arrive while those from China take just six months, partly due to considerable idle capacity in machine production. Purchasing Chinese machines brings lasting dependencies: the set-up, operation and maintenance of the machines requires technical support from trained Chinese experts.

Patents, performance and novel battery technologies

China dominates patents around advanced LFP materials capable of fast-charging and higher energy density. These patents could provide challenges for players developing LFP materials in other markets. In addition to the material itself, Chinese companies such as CATL and BYD have pioneered battery pack-level innovations including cell-to-pack (CTP) which have increased the energy density and competitiveness of their LFP batteries. There has been limited uptake of CTP outside of China, which may also be influenced by patents, adding other technological and performance hurdles to the rest of the world.

Substitution options

Beyond conventional LFP production processes, alternative methods of producing LFP are under development. Hyundai and Kia launched a project to produce LFP directly without precursors. Nano One is also working to eliminate the precursor production process with its One-Pot process, aiming to reduce cost, energy usage and waste generation. LG Chemical also announced its precursor-free cathode material aiming to have mass production in 2025, designed for nickel-based materials initially but potentially opening to LFP later. Initial information suggests that this process enables direct LFP production from metals, eliminating the need for pCAM production and metal sulphates, thereby reducing dependency on Chinese supply chains.

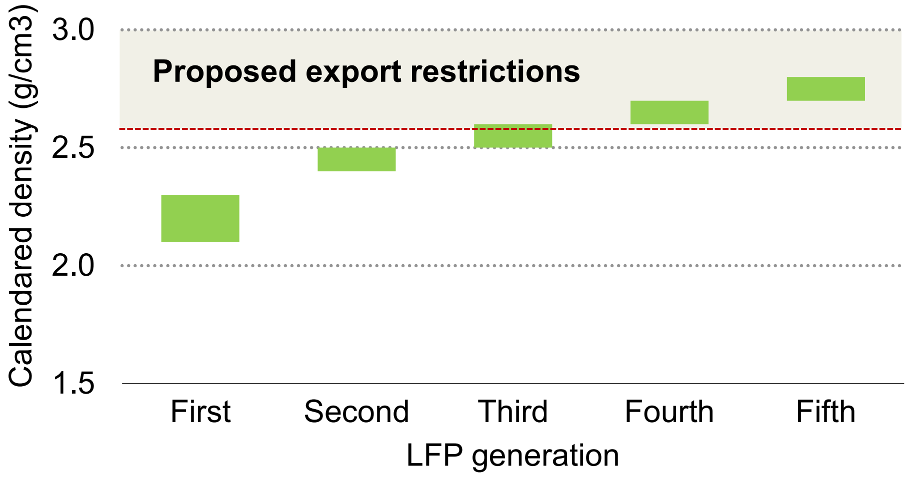
China's LFP technology export restrictions: What would do they mean for building out diversified LFP supply chains?

In January 2025, China's Ministry of Commerce proposed a new set of export licence restrictions on technologies related to LFP production and lithium processing, which were under public consultation until February 2025. The proposed LFP restrictions currently focus on technologies related to the production of the advanced fourth generation of LFP cathode material, which exhibits higher energy density and faster charging capabilities. The proposed restrictions do not necessarily prevent the export of the advanced LFP materials itself if produced in China.

The technology restrictions are broadly defined including patent rights and licensing, technical services, and transfer of technology by any other means. Fourth-generation LFP materials are higher density, requiring advanced manufacturing processes and additional stages to produce. Given the broad and somewhat vague definitions, patents, technology and equipment used to manufacture these materials could also fall under the restrictions.

Supply of the fourth-generation LFP is understood to be in deficit even in China as only a few suppliers have the capability to produce it, despite the oversupply of conventional LFP. The leading supplier is Chinese company Fulin Precision Machining, whose production in 2024 was almost all fourth-generation LFP, being the sole supplier of fourth-generation LFP to CATL for its fast-charging Shenxing battery. Other companies such as Hunan Yuneng and Lopal are anticipated to ramp up output of fourth-generation LFP in 2025.

LFP technologies affected by proposed export restrictions



Notes: g/cm^3 = grammes per cubic centimetre. Based on current proposals. Export restrictions affect LFP with density ≥2.58 g/cm^3.
Source: IEA analysis based on Benchmark Minerals Intelligence.

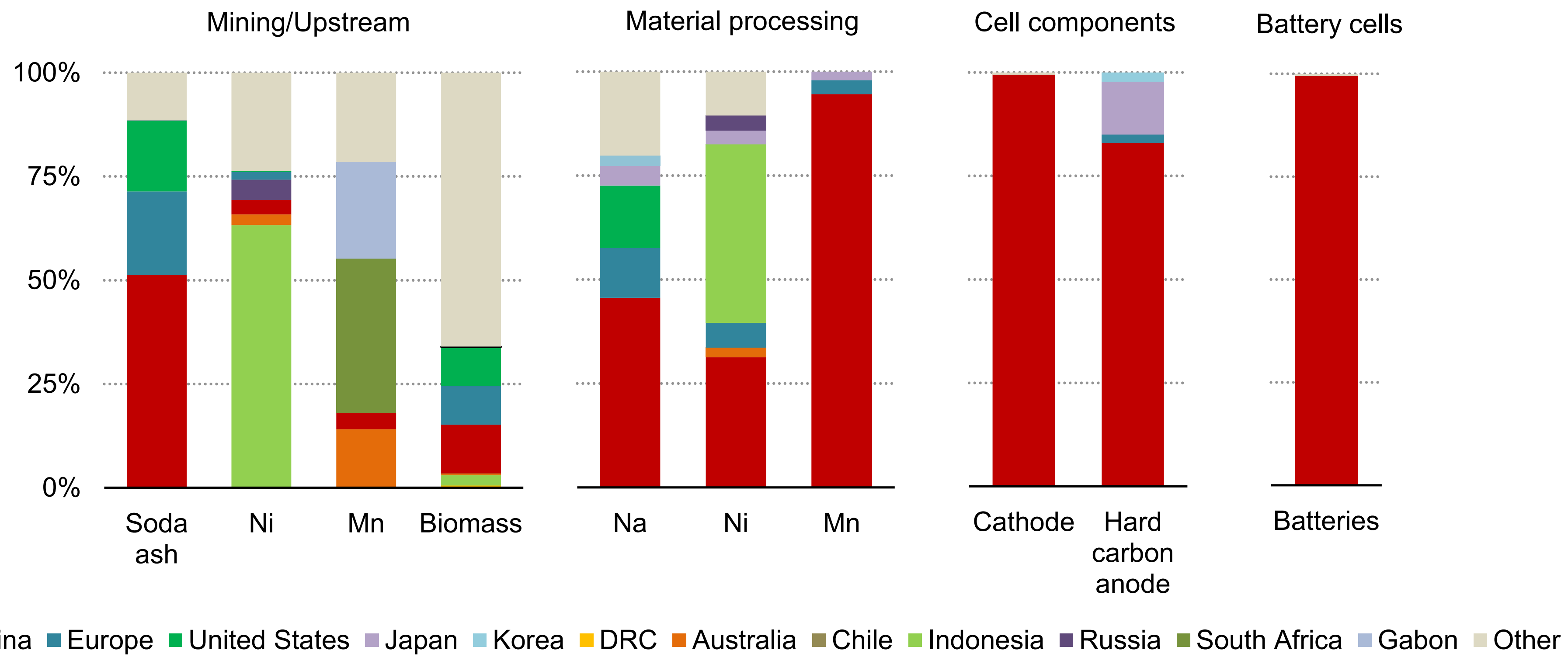
If enacted, the proposed export restrictions may have significant implications for Chinese companies' plans to produce advanced LFP overseas. Fulin Precision Machining has no announced plans to do so. However, Hunan Yuneng, Lopal and others with advanced LFP capability have plans for LFP production facilities overseas. If the proposed export restrictions come into force, it could affect these companies' plans to produce advanced LFP materials at these facilities.

The proposed export restrictions and rising barriers to technology transfer for advanced LFP cathode materials are likely to hinder the development of diversified LFP supply chains as these materials remain highly sought after by battery cell producers and automakers (although there are reports that Korean cathode manufacturers have developed fourth-generation LFP independently). The broad and sometimes vague aspects of the proposed restrictions leave considerable room open for stricter controls which could slow the development of diversified LFP. For instance, the application of LFP patents could be enforced in ways that potentially cause issues even for LFP products developed independently of China.

Overall, the proposed export restrictions for LFP should be taken seriously. Original equipment manufacturers and battery manufacturers have already started factoring in increased procurement risk of LFP cathode material from China. Despite export of fourth-generation LFP cathode material products currently being allowed within the regulation, this could change in the future. Automakers and battery cell producers need to factor in these risks as they seek to successfully develop more diversified supply chains.

The downstream sodium-ion supply chain is dominated by China, but the upstream is more diversified than lithium-ion batteries with the United States and Europe playing major roles

Geographical distribution of the sodium-ion battery supply chain, 2024

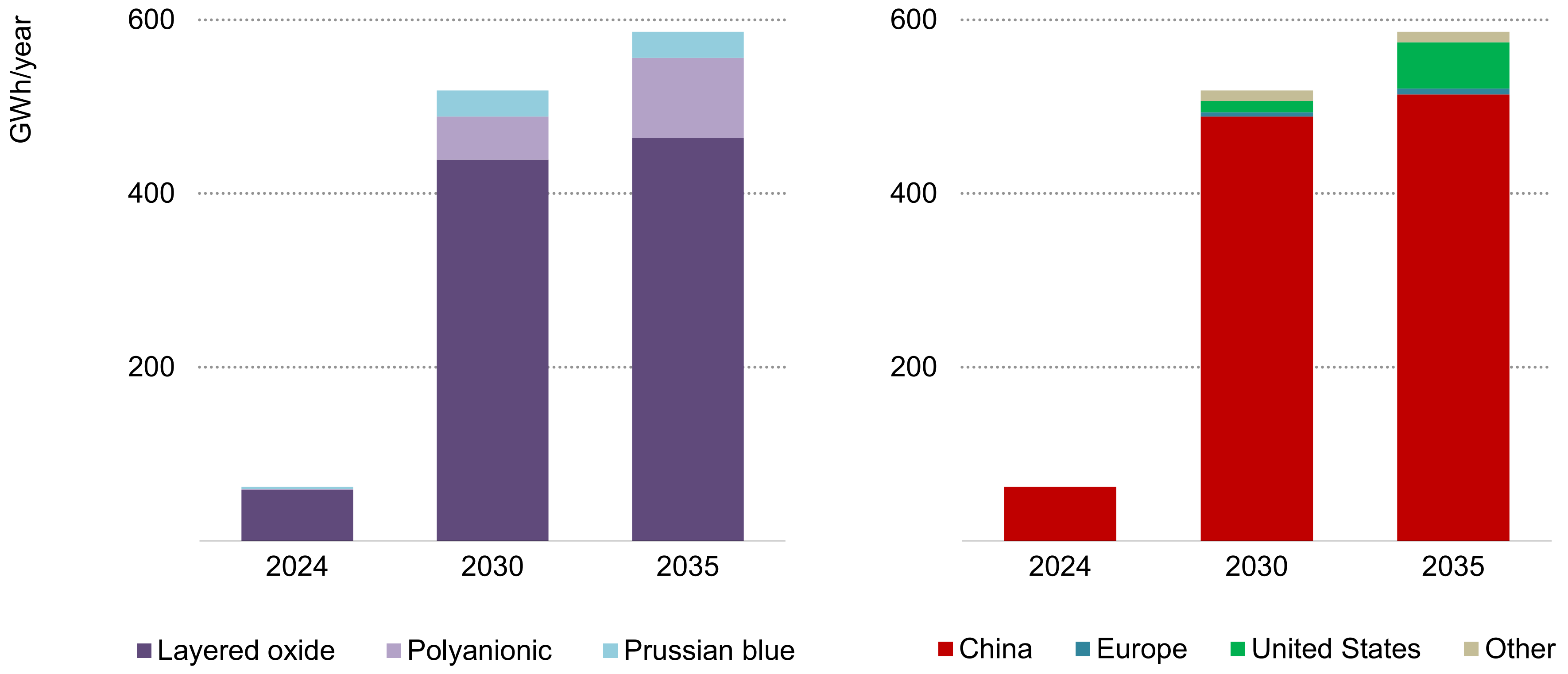


Notes: DRC = Democratic Republic of the Congo; soda ash = sodium carbonate; Na in material processing = caustic soda (sodium hydroxide); Ni = Nickel; Mn = Manganese. Hard carbon anode production capacity also includes some soft carbon anode capacity. Biomass includes residues from grain, oil, protein, and sugar crops as well as from managed forests and wood processing.

Sources: IEA analysis based on USGS (2025), Mineral commodity summaries, Benchmark Mineral Intelligence, Food and Agriculture Organisation.

Sodium-ion gigafactory development is set to be driven by China, and layered oxides are emerging as the dominant cathode chemistry

Sodium-ion battery cell production capacity by cathode chemistry and geography, 2024-2035



Notes: GWh = gigawatt-hours. Gigafactory capacity data based on existing and announced projects.
Source: IEA analysis based on Benchmark Minerals Intelligence.

Mapping the sodium-ion battery supply chain

Sodium-ion batteries are emerging as the first commercialised battery chemistry viable for EVs and storage that does not contain lithium. Sodium-ion has a slightly lower energy density than LFP, but it uses the same battery manufacturing process, allowing for easy adaptation in gigafactories. CATL and BYD are already leading sodium-ion production for both EVs and storage. The key advantage of sodium-ion is that it relies on considerably fewer critical minerals than lithium-ion batteries. The leading sodium-ion anode and cathode materials contain no graphite, lithium or cobalt and less nickel than the leading nickel-based lithium-ion cathodes. Moreover, sodium-ion is able to use aluminium anode current collectors, unlike lithium-ion, significantly reducing the copper intensity and potentially offering improved safety for transportation. Finally, sodium-ion exhibits superior low-temperature performance compared with lithium-ion. Sodium-ion cells are well suited to applications in energy storage, low-range EVs and two- and three-wheelers. Despite the economic advantages of sodium-ion having considerably diminished with the decline in lithium prices since 2023, its other advantages such as reduced critical minerals dependence and low-temperature performance are continuing to drive development.

Sodium-ion anode materials

Sodium-ion cannot use graphite anodes, so instead uses alternative carbon materials, predominantly hard carbon and some soft carbon. Soft carbons are formed from pyrolysis of fossil fuel feedstocks such as tar, petroleum or pitch, leading to high emissions intensity. Hard carbons are the leading sodium-ion anode material and are produced by pyrolysis of biomass or phenolic resins derived from by- or waste-products from agriculture, food, textile or manufacturing industries. As a result, the feedstock for hard carbon anodes is low cost and abundant – China, Europe and the United States together only account for 30% of global biomass supply. However, there is significant processing required for the production of hard carbon anodes, which can increase costs despite the cheap feedstock.

Current hard and soft carbon anode production capacity is dominated by China with almost 85% of global capacity in 2024. Japan holds considerable capacity with almost 15%. Europe (Finland) and Korea have around 2% each. Despite the presence of some experienced anode producers such as BTR, the majority of hard and soft carbon anode capacity is from companies that have never produced battery-grade anode material before, indicating it may take longer to scale production. Further, based on the project pipeline, there is an implied deficit of hard carbon capacity compared with sodium-ion battery cell production capacity, demonstrating that hard carbon anode development may become a bottleneck for sodium-ion battery development. Nevertheless, if there are signals of growing demand, experienced anode producers could scale hard carbon anode production relatively quickly.

Sodium-ion cathode materials

Sodium-ion cathodes rely on a new supply chain for sodium instead of lithium, which is predominantly sourced from soda ash. Soda ash (sodium carbonate) is globally distributed and abundant, primarily found in hard rock deposits (known as trona rock) and sodium-carbonate-rich brines. These sources are known as natural soda ash. The largest proven deposit is found in Wyoming in the United States.

Soda ash can also be produced from salt-rich brines (sodium-chloride-rich brines), in a process using ammonia and limestone – this is known as synthetic soda ash. Synthetic soda ash can be low cost; however, its production is highly energy- and emissions-intensive and generates considerable harmful waste. Synthetic soda ash production is dominated by China, which produces around half of global soda ash supply, while the United States leads natural production with almost 20% of total soda ash supply. Europe is also a major producer with 20% of production, driven by Türkiye, which produces almost 80% of this from natural soda ash.

Sodium hydroxide (caustic soda) is the refined version of soda ash, which is commonly used as the sodium-ion cathode precursor. Production of sodium hydroxide is also led by China with around 45% of global production in 2024, though the United States is also a major player with 15% of production followed by Europe with over 10%.

Sodium-ion cathodes are distinguished into three material classes: layered oxides, polyanionic and Prussian blue analogues (PBAs). The same class as NMC for lithium-ion, leading layered oxide cathodes for sodium-ion typically utilise manganese, nickel and small quantities of other metals such as titanium. Layered oxides have lower nickel intensity than nickel-rich NMC chemistries for lithium-ion. PBAs are the least critical-mineral-intensive sodium-ion cathode chemistry, typically based on iron and manganese. However, they have lower energy density, and their production process may have some scalability challenges. Polyanionic sodium-ion cathodes typically rely on vanadium, which is expensive, though may provide increased high-power capability.

Based on the current sodium-ion gigafactory pipeline, layered oxides are emerging as the dominant cathode for the industry with 95% of global capacity in 2024, 85% in 2030 and 80% in 2035. However, there is also significant growth anticipated for polyanionic cathodes from just 2% in 2024 to over 15% in 2035. This is largely due to the anticipation of the emerging vanadium-free polyanionic cathode chemistry NFPP (sodium iron phosphate-pyrophosphate), which is emerging as a potential competitor to LFP batteries for low-range EVs and energy storage, with superior low-temperature performance. Nevertheless, given the preference for layered oxide cathodes for sodium-ion, battery-grade manganese sulphate and nickel supply chains will likely be important for sodium-ion development going forward, both of which have significant concentration challenges.

Mapping the solid-state battery supply chain

All solid-state batteries (ASSBs) represent a possible technology step change for battery energy density and safety, enabling greater EV ranges. However, these potential advantages still need to be proven at battery pack scale. There also remains significant production challenges for scaling production of ASSBs at competitive costs and low defect rates. ASSBs typically utilise conventional lithium-ion cathodes such as NMC with a solid electrolyte, which enables the use of a lithium metal anode. Lithium metal anodes are the highest possible energy density anode for lithium-ion batteries, potentially enabling energy densities up to 70% higher than the current leading lithium-ion batteries.

There are many variations of solid electrolytes, with sulphide-based and oxide-based electrolytes emerging as the leading contenders. Sulphide-based electrolytes typically rely on phosphorous and lithium sulphide. As a result, some of the phosphate supply chains critical for LFP batteries are also important for ASSBs. Lithium sulphide production is currently in its infancy and could prove a critical bottleneck to the development of sulphide-based electrolytes. Leading oxide-based electrolytes rely on materials including lanthanum and zirconium, and their production could become a future constraint. Both are not immediate concerns as they are considered by-products of other mineral mining. Lanthanum is currently in oversupply and mined with other rare earth elements which have larger demand, though it is predominantly mined in China leading to new potential concentration risks. Zirconium is mined as a by-product of titanium and other heavy metal mining, which have established supply chains. Despite currently not being subject to a supply limitation, if ASSB deployment proceeds fast as targeted by several companies, their supply could quickly become a potential bottleneck.

Finally, lithium metal anode production provides its own significant challenges. Theoretically ASSBs can be “anode-free”, a configuration where there is no excess lithium in the anode and instead only the lithium in the cathode and electrolyte is used to build an anode during operation. However, this is highly technically challenging to realise, therefore, lithium metal anodes are typically required. ASSBs require thin lithium metal anodes for significant energy density advantages. However, the production of thin battery-grade lithium metal anodes at scale is also technically challenging, costly and has considerable safety challenges given the reactivity of lithium metal. China is set to have over 90% of battery-grade lithium metal production capacity in 2025, while North America is the second-largest region from just two companies, Albemarle and Arcadium Lithium.

Policy implications

Given the growing competitiveness and market share of LFP cathodes, coupled with the LFP technology export restrictions proposed by China, it is becoming increasingly important for policy makers to pay close attention to developing a diversified LFP supply chain.

Policy measures on both the supply side and the demand side are important for successful development of diversified LFP supply chains. A first challenge is to address the equipment costs and lead time challenges. Providing targeted subsidies and incentives to new LFP equipment/machinery producers, supporting their increase of production capacity, can be effective to both reduce lead times and reduce equipment and machinery costs through economies of scale. Building a group of domestic or international equipment producers to co-ordinate production of components and equipment can also realise scale advantages more quickly.

Second, provide financial support both at direct capex and opex level or through other de-risking measures, such as loan guarantees or lowered interest rates, for domestic LFP cathode material and raw material input producers. These measures can help incentivise private investment and facilitate increases in production, which is crucial to building domestic LFP material production expertise. Supporting industrial LFP research and development (R&D) efforts is also crucial to develop competitive fourth-generation LFP cathode material. The same measures are essential to support strategic critical mineral mining and refining projects for key material inputs such as battery-grade manganese sulphate and battery-grade PPA. Supporting refining project investments near key reserves, for instance Morocco for phosphate, can help minimise transportation costs. Co-ordination among players can also support bringing raw material costs down.

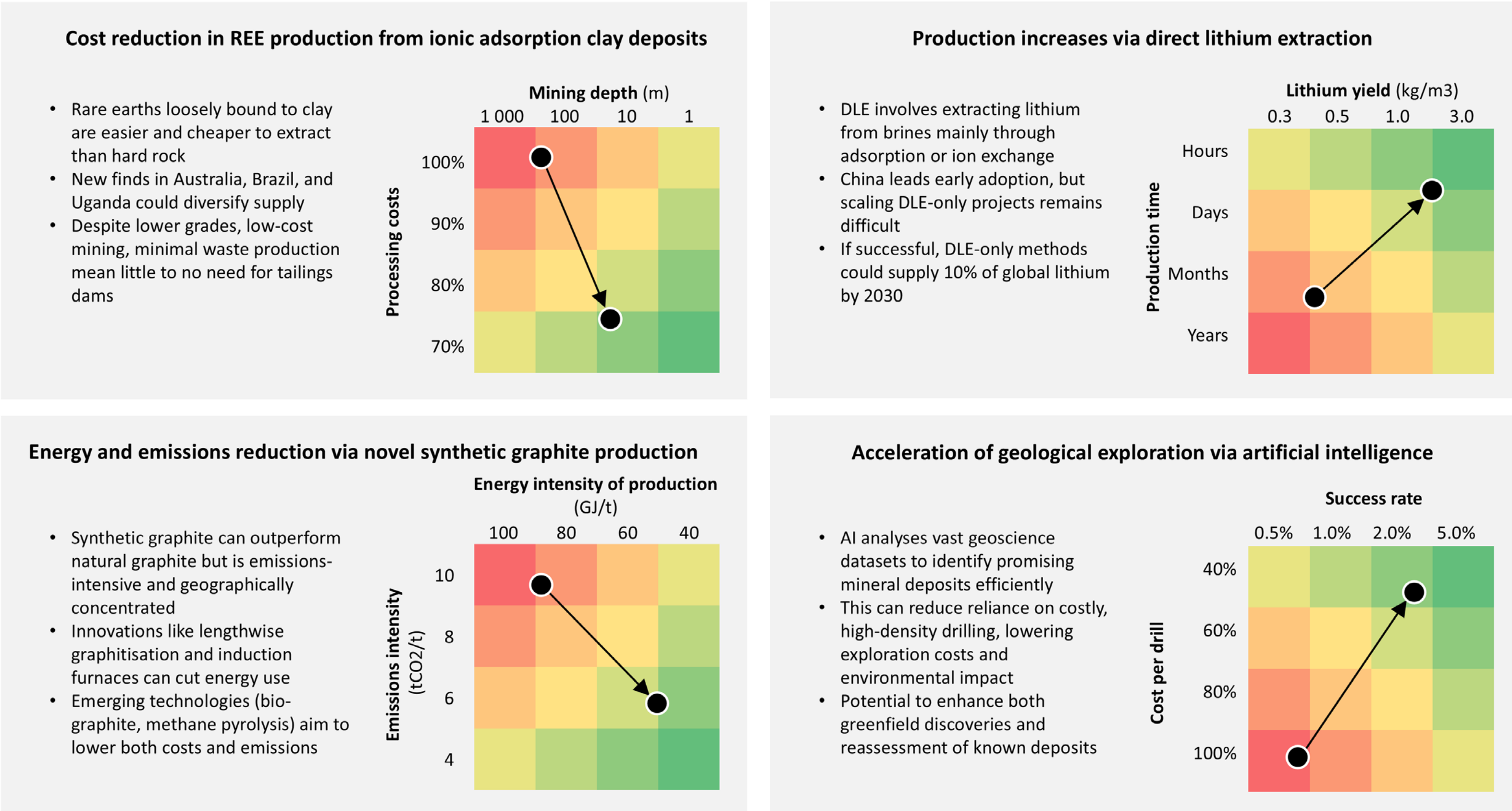
On the demand side, it is also important to simultaneously stimulate domestic LFP demand, providing incentives to use LFP cells made using domestic LFP material, raw material inputs or equipment, making domestic or diversified LFP more competitive. Finally, facilitating co-ordination among diversified players and countries is important to more effectively negotiate in the event any export controls are enacted. Co-ordination among key diversified players acting as a group can also be important for patent negotiations in the event of patent disputes.

All these measures are also relevant for supporting the development of diversified sodium-ion and solid-state battery supply chains. Sodium-ion also presents significant opportunity given its more diversified upstream. Since biomass is widely available, there is also less restriction on raw material inputs, but supporting the development hard carbon production capacity is key. For ASSBs, focusing on developing lithium metal anode and lithium sulphide production capacity are key priorities.

Supply-side technology innovation (mining, refining, recycling) to promote diversification

New technologies in the upstream and midstream segments will be crucial to sustainably scale up supplies in line with demand

Potential improvements in selected indicators through the use of novel supply-side technologies



Notes: REE = rare earth element; m = metre; DLE = direct lithium extraction; kg/m^3 = kilogrammes per cubic metre; tCO_2/t = tonnes of carbon dioxide per tonne; GJ/t = gigajoules per tonne; AI = artificial intelligence.

Why supply-side technology innovation matters – scaling up the supply of critical minerals more efficiently and sustainably will require novel technologies

Often when thinking of innovation and critical minerals, the dialogue focuses on demand-side (end-use) innovations, such as improving material efficiency or developing new battery chemistries and designs that rely on fewer critical minerals. Thanks to targeted investments and R&D efforts, demand-side innovations have made tremendous progress in recent years. Silicon intensity for utility-scale solar photovoltaic (PV) dropped by nearly 55% between 2015 and 2024, prices of lithium-ion battery packs fell by 75% from over USD 460 per kilowatt-hour (kWh) to USD 115/kWh over the same period, and new battery technologies such as LFP and sodium-ion are promising sizeable reductions in mineral demand.

In addition, the continued growth in mineral demand in the coming decades calls for substantial contributions from supply sources that are sustainable and minimise losses and waste. However, progress on upstream and midstream, or “supply-side”, innovations has been lagging. Building truly resilient and sustainable mineral supply chains will require efforts to scale up new technologies that can increase supply volumes, improve the energy efficiency of production processes, and reduce water consumption, waste generation and emissions all along the supply chain.

These innovations can help achieve various policy goals: improving security of supply, enhancing production and operational efficiency, boosting yield rates, lowering environmental and social impacts, and shortening project timelines. Examples include the lowering of energy and capital intensity of rare earths production by leveraging ionic adsorption clay (IAC) deposits; boosting overall supply levels for lithium through the commercialisation of direct lithium extraction (DLE); reducing energy and emissions intensity for synthetic graphite production through novel technologies; accelerating exploration times with the use of artificial intelligence (AI).

In this section, we explore some emerging supply-side innovations with the potential to transform or modernise various aspects of mineral production. For mining, we look at direct lithium extraction (DLE), in situ recovery, ionic adsorption clays, and re-mining of tailings and mine waste from existing mine locations. For refining, we elaborate on novel synthetic graphite production, sulphide ore leaching, new rare earths separation techniques and microwave-based calcination. For secondary supply or recycling, we examine advanced sorting and novel recovery techniques. The section also discusses the potential applications of AI in mineral extraction using a few case studies. The section concludes by shedding light on the bottlenecks that can impede scaling up novel technologies in diversified regions, particularly in the midstream segment, and analysing the policy mechanisms that can boost progress on supply-side innovations.

Innovations along the supply chain – new technologies in mining, refining and recycling

Mining

The mining sector plays a foundational role in the energy technology manufacturing supply chain, yet many of its processes have remained consistent for decades. This has presented challenges in improving energy efficiency and reducing waste and emissions. However, there are some promising developments that are driving innovation in critical minerals mining.

Direct lithium extraction

Direct lithium extraction (DLE) is an innovative technology that can unlock vast unconventional resources by extracting lithium from both existing brines and geothermal and oilfield brines with lithium concentrations that are typically considered too low for traditional evaporation methods to process economically.

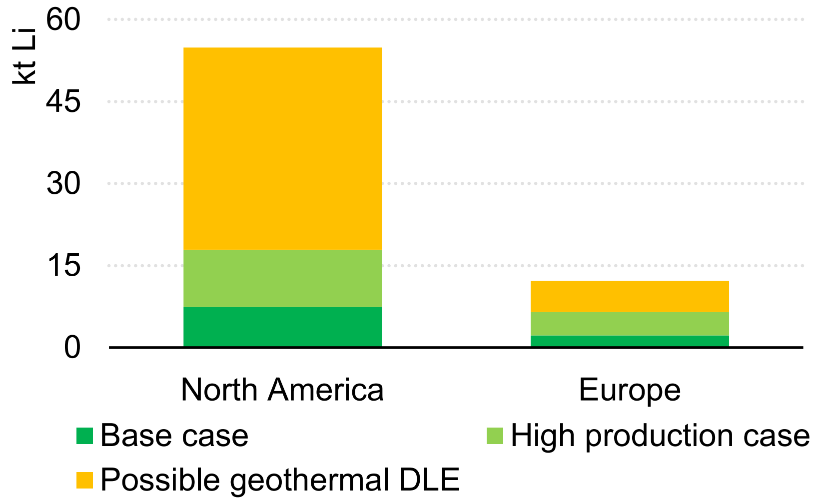
DLE operates by pumping lithium-rich brine from reservoirs, selectively capturing lithium mainly via adsorption or ion exchange methods, and then purifying it into lithium chloride or using electrolysis and processing the chemical into battery-grade lithium carbonate or lithium hydroxide. After extraction, the brine is reinjected to sustain reservoir pressure. To unlock the potential of lithium brines, extensive research and testing is being conducted on DLE technologies, and other promising alternatives to adsorption and ion exchange include solvent extraction, membrane technologies, and electrochemical and chemical precipitation.

Compared with traditional processes, DLE can offer a faster, more efficient and environmentally promising approach to lithium production, but faces scalability and environmental hurdles of its own, such as freshwater consumption, on its way to widespread adoption. The choice between the DLE methods depends on brine characteristics. Adsorption is effective for high-lithium-concentration brines, using fewer chemicals, offering greater scalability and having lower upfront costs. Meanwhile, ion exchange is optimal for lower lithium concentrations or complex brines with competing ions such as sodium and magnesium, but it requires careful management of potential chemical waste. Despite its higher initial costs, it can be more economical for low-lithium brines owing to its precise ion capture capability. Brines with higher lithium concentrations (above 150 milligrammes per litre) could shorten processing time and reduce energy and reagent costs.

China has several brownfield brine operations, and Arcadium Lithium has been using adsorption DLE at its existing brines in the Hombre Muerto flats in Argentina. While there are currently a few brownfield brines and no commercial geothermal and oilfield DLE projects under operation, several are advancing towards construction and commercialisation phases, including pilots and larger demonstration and optimisation plants. Vulcan Energy is proceeding with its project in the Upper Rhine Valley in Germany. It is expected to commence its operation with 24 kt of lithium hydroxide production per year through adsorption DLE technology. In December 2024, Rio Tinto announced an investment of USD 2.5 billion for the Rincón Lithium Project that started using DLE in production well fields at its starter plant in November 2024. In May 2024, SQM and Codelco announced a joint venture agreement for the use of DLE technology in the Salar de Atacama, with operations expected to begin soon.

In recent years, interest in the technology has been growing. The European Union and several European countries have collectively funded geothermal lithium research and pilot projects, including EuGeLi, UnLimited, LiCORNE (partnering with SQM) and Li+Fluids, to leverage shared infrastructure and thus advance geothermal lithium technologies and industrial scalability. To advance DLE technology and geothermal lithium extraction, the US Department of Energy committed over USD 15 million in 2022 to support R&D in this field. DLE is also mentioned as a sustainable and environmentally responsible way to extract lithium in the National Lithium Strategy of Chile, where water security is crucial. China has proposed a new set of restrictions on the export of technologies which includes DLE in January 2025.

Mined lithium supply with announced geothermal DLE projects in North America and Europe, 2035



Source: IEA (2024), The Future of Geothermal Energy.

So far, brines in Argentina and China are at the forefront of DLE-based production. These early projects combine DLE with traditional evaporation ponds, and now account for nearly 10% of global lithium supply. Scaling up DLE-only technologies, which bypass evaporation ponds altogether, has presented significant challenges. Based on the current project pipeline, DLE-only production could reach 10% of global lithium supply by 2030 (see Chapter 2). If emerging applications, such as geothermal brines, prove viable, that share may rise further, with the potential to boost lithium production in North America, Europe and others.

In situ recovery

In situ recovery, known as solution mining or in situ leaching, is a method that leaves the ore in the ground, recovering minerals by dissolving and pumping pregnant solution out to the surface without physical excavation or fracking.

As it works best in permeable sandstone deposits, it is widely used in uranium mining. While not yet widespread in copper mining, a few projects are being developed in the United States and Australia where oxide and secondary sulphide deposits are present. Florence Copper is expected to produce London Metal Exchange (LME) Grade A copper metal using this technology in Arizona by the end of 2025. The use of this method could potentially be extended to other minerals such as nickel, cobalt and rare earth elements.

The technology avoids open-pit or underground mines, leading to energy savings, lower emissions and reduced water consumption. It also does not require waste stockpiling or tailings dams, thus resulting in lower capital needs and a smaller environmental footprint.

Ionic adsorption clay

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 concentration of rare earths. Rare earth-bearing minerals found in these rocks include monazite, xenotime, bastnaesite, allanite, titanite and apatite. The interest in this form of deposit comes from the expectation that extracting rare earths, which are loosely bonded to the surface of rocks, may be relatively simpler, less energy-intensive and more cost-effective than obtaining them from deeper hard rock formations. Additionally, this method could also avoid the radioactive by-products associated with traditional mining processes for these minerals (see Chapter 2).

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 heavy rare earth elements (HREEs) are dominantly sourced from Chinese regolith-hosted IADs or clay deposits in Myanmar and the Lao People's Democratic Republic (Lao PDR), in which the elements are inferred to be weakly adsorbed onto clay minerals. Similar deposits elsewhere might provide alternative supply for these minerals, but the adsorption mechanisms remain unclear.

Traditional REE projects based on hard rock developments are capital-intensive, often costing USD 1 billion to USD 2 billion to build, making them difficult for junior miners to fund. In recent years, junior miners have shifted focus from highly capital-intensive hard rock REE projects to low capital-intensity IAC projects which are enriched in HREEs. Despite in situ grades being lower than hard rock projects, the mining process is simpler, leading to substantially lower capital expenditure and operating costs. Most clay operations involve digging or scraping of only the top twenty metres of earth, as opposed to hard rock sources which require blasting deep deposits. Clay material is soft and easier to process, whereas hard rock material needs to be crushed and ground in large quantities. For processing, IAC projects use less energy-intensive processing methods like heap or vat leaching at atmospheric temperature, compared to high-temperature roasting and acid leaching for hard rock. Finally, clay waste is generally inert and can be backfilled into the mining area, eliminating the need for tailings dams or dry stacking.

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. 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 2024, Appia Rare Earths & Uranium announced a maiden mineral resource estimate for its ionic adsorption clay PCH project in Goiás, Brazil. The economic viability of IAC deposits remains uncertain, but they can be attractive from perspectives of capital intensity, ease of working, carbon intensity and radioactive waste management.

Reprocessing of tailings and mine waste

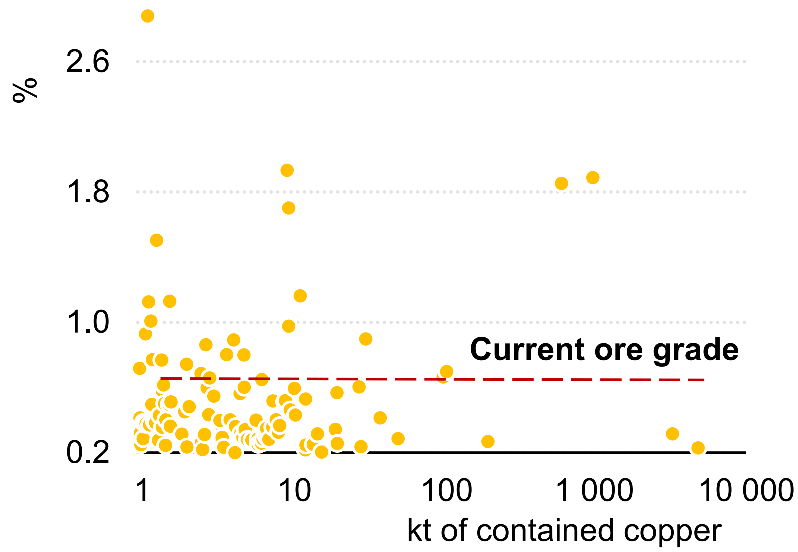
Mining waste includes all materials generated during the extraction and processing of ore into commercially viable products. It can come in many forms, such as waste rock produced while accessing the ore deposit, tailings generated when separating desired materials from the rest, and mine drainage water, which could be surface or groundwater draining from active or abandoned mines. Sometimes there are minerals left within this mine waste that had low economic value at the time of extraction and therefore were not considered economically viable to recover. It may have also been the case that the appropriate technology was not available at the time of original recovery. However, increasing demand for minerals in energy technologies have prompted a re-evaluation of the financial feasibility of recovering these minerals, positioning mine waste as a potential new source of supply.

Chile provides an example. Over the past 20 years, the average ore grade for copper in Chile has declined by a third from 0.9% to 0.6%. In 2005, there was only 1.6 million tonnes (Mt) of contained copper in tailings that was higher than primary ore grades. In contrast, today there are 100 tailings sites with ore grades that exceed those of primary production, totalling 2 Mt of contained copper. This indicates that extracting copper from these tailings could be economically attractive. If this trend continues, by 2050 there could be 5.6 Mt of contained copper that exceeds the ore grade found in primary mining operations, almost three times higher than today.

Several factors influence the economics of reprocessing mine waste. Current prices of the minerals in question play a significant role, with periods of higher prices providing larger financial incentive to extract minerals from this waste. Recovery efficiency also impacts the financial viability, as a smaller quantity of potentially recoverable minerals means lower rates of return. Environmental risks associated with mine waste also impact the business models. The liability and costs of safely storing and managing mine waste are significant, particularly in jurisdictions with stringent regulations for mine site closure and rehabilitation. By reassessing mine waste as a potential resource, companies could offset these costs.

Reprocessing mine waste can not only reduce financial burdens associated with mine and tailings closure, but also mitigates environmental risks, such as acid mine drainage and tailings failures. Reprocessing waste could also help avoid escalating compliance costs resulting from increasingly stringent environmental standards.

Average contained copper found in tailings versus ore grade in Chile



Source: IEA (2024), Recycling of Critical Minerals.

Refining

Refining is the most energy-/electricity-intensive segment of the critical minerals production process, leading to some of the highest levels of greenhouse gas (GHG) emissions among the entire value chain. Several innovations on the horizon have the potential to reduce the energy intensity involved in mineral refining.

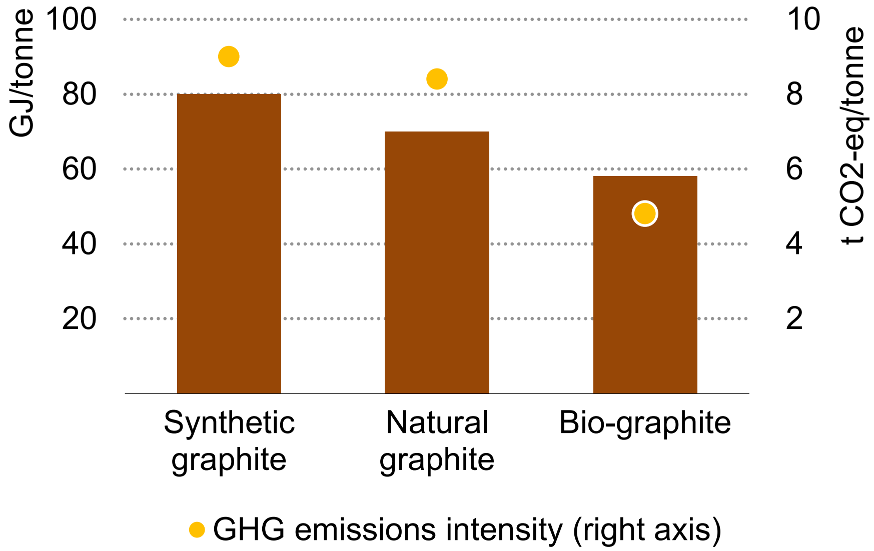
Novel synthetic graphite

Battery-grade synthetic graphite is made from high-temperature treatment of a blend of lower-purity carbon-based raw materials such as petroleum coke, coal tar pitch or oil. This creates a uniform carbon structure suited for high-performance, fast-charging, long-lasting lithium-ion battery anodes. It is purer than natural graphite in terms of carbon content and tends to behave more predictably, making it a competitive alternative to natural graphite. However, the production process is highly energy-intensive (thus up to four times more carbon-intensive than natural graphite anode production) and can be significantly more costly than processing of natural graphite. The vast majority of battery-grade global synthetic graphite supply today originates from China. Within China, Inner Mongolia accounts for roughly a fifth of the supply. The graphitisation of coke products into synthetic graphite is the largest source of energy consumption and the carbon emissions increase substantially if fossil-based electricity is used for this process, especially with coal-based electricity such as in Inner Mongolia. These issues require innovative technologies to produce synthetic graphite in a more environmentally friendly way.

Some solutions being studied include "lengthwise graphitisation" that uses the resistance of the carbon material itself to convert electric energy into heat energy which graphitises the material. This method reduces the energy consumption for heat generation and the time for graphitisation. Tokai Cobex is currently investigating the scalability of this technique to produce synthetic graphite of over 99% purity at its French R&D centre. Another promising technology uses induction furnaces to use the material's inherent conduction properties achieving the required temperatures in shorter times than regular ovens/furnaces. Vianode in Norway and Novonix in the United States are set to become some of the first producers of graphite using the induction furnace technology.

Other technologies with relatively lower technology readiness levels (TRLs) are "bio-graphite", which uses amorphous carbon in biomass to produce battery-grade graphite, and methane pyrolysis, which uses solar-thermal energy or joule heating to achieve methane pyrolysis to produce hydrogen and synthetic graphite. CarbonScape in New Zealand is working on bio-graphite and Molten Industries in the United States is working on methane pyrolysis. The overall aim of all the novel technologies is to significantly reduce the emissions footprint of producing synthetic graphite, while also achieving gains in processing time and costs.

Illustrative levels of energy and GHG emissions intensity for natural, synthetic and bio-graphite produced from biochar



Notes: t CO_2-eq/tonne = tonne of carbon dioxide equivalent per tonne. This figure is meant to be illustrative of the impacts of graphite production through different pathways, and actual data for an individual project may be different.
Source: IEA analysis based on You, Hui et al. (2024)

Sulphide ore leaching

Conventional processing techniques for copper are pyrometallurgy used for sulphide ores, which requires huge capital investments and results in non-trivial environmental impacts. From the perspectives of cost-competitiveness and environmental impacts, the solvent extraction electrowinning (SxEw) method, which directly produces refined copper from oxide ores through hydrometallurgy, has been widely applied as the preferred choice since the 1980s. However, hydrometallurgy was not considered suitable for sulphide ore processing due to its slow leaching rates, especially for primary sulphide ores. In recent years, as ore grades have been depleting, interest in sulphide ore leaching using chemical solutions is gaining traction. While there are several specific technologies that can be used for sulphide ore leaching, no single technology can be applied to all mines and will need to be tailored to fit each situation. Several mining companies such as Ceibo, Jetti Resources and Nuton (a subsidiary of Rio Tinto) are working to improve and commercialise the use of sulphide ore leaching.

Once sulphide ore leaching technology becomes commercially viable, it may increase production by utilising ores that were so far not being processed and will also lower water consumption and hazards that are linked with tailings. The challenges of sulphide ore leaching include lower recovery rates, longer cycle times and fewer by-products produced compared with conventional concentrator or pyrometallurgy methods, but major strides in sulphide ore leaching technology are being made recently.

Novel REE separation technologies

In recent years, research efforts dedicated to the development of novel rare earths separation technologies have gained significant momentum. Separating individual REEs is a challenging task given their similar properties and oxidation states, and their occurrence as a mixture of elements within mineral deposits. Presently, solvent extraction is the predominant commercial process for separating rare earth concentrates into high-purity materials; however, its challenges include high costs, high energy inputs and significant waste products that include large volumes of organic solvents and even some radioactive waste. Therefore, the traditional processes can lead to significant environmental and health risks, highlighting the need for innovative techniques that reduce these impacts. Investigations into several novel approaches such as selective precipitation, selective crystallisation, selective dissolution, the application of efficient N-heterocycle-based extractants in solvent extraction processes, and dual-ligand separation systems are being made. While new ligands and separation methods are driving innovation in this field, there is a need to bridge the gap between fundamental and applied research. Efforts in conducting multistage separations or larger-scale demonstrations will be required for these technologies to begin replacing incumbent processes.

Microwave-based calcination

Microwave heating, unlike conventional heating methods, transfers energy directly to the target material, which then converts this energy internally to heat, eliminating the need for high-temperature heat generation sources, resulting in reduction of cost and emissions. While it could be used in various industries requiring high-temperature processes, companies such as Microwave Chemical are focusing on developing the technology for critical minerals such as lithium. Conventional lithium processing includes a calcination step for the lithium concentrate at more than 1 000 ^{0}C, but technology developed by Microwave Chemical has proven successful in dissolving it at 300 ^{0}C though only on a laboratory-scale set-up.

Compared with conventional methods, the new technology could reduce capital and operational costs by around 70% and CO_2 emissions by around 90% if it achieves commercial scales. Since this technology has a lower TRL, the company has been trying to de-risk it through commercialisation test.

Recycling

As the International Energy Agency's (IEA) 2024 report on recycling of critical minerals highlighted, innovative critical minerals recycling technologies have the potential to meaningfully address supply chain vulnerabilities and environmental concerns associated with primary extraction.

Advanced sorting

Traditional sorting methods, such as density and magnetic separation, are often insufficient for handling the complex compositions of modern waste materials. Recent advances in automated sensor-based sorting, particularly hyperspectral imaging (HSI) and artificial intelligence, are significantly improving efficiency. HSI differentiates materials based on their spectral signatures, enabling precise separation of critical minerals from electronic waste, while AI-driven systems adapt to material variations in real time, reducing processing errors and increasing throughput.

X-ray fluorescence sorting has become commercially viable, allowing for rapid identification of elemental compositions, which is particularly valuable for multi-alloy waste streams. Additionally, laser-induced breakdown spectroscopy is being used for real-time composition analysis, ensuring high-quality outputs by identifying impurities before materials enter downstream recovery processes. The integration of robotics and computer vision further enhances sorting accuracy, reducing reliance on manual labour and making the recycling process more scalable.

Novel recovery techniques

Refinements in hydrometallurgical processes are improving the recovery of key battery materials such as lithium, cobalt and nickel. Selective leaching and advanced separation membranes are increasing efficiency while reducing chemical consumption. Despite these advancements, widespread commercial adoption remains limited, largely due to cost constraints.

Plasma arc recycling presents an alternative for extracting metals from complex waste, particularly in electronics recycling, where material compositions vary significantly. Compared with traditional smelting, plasma technology offers lower emissions and greater adaptability, making it a promising option for recovering high-value elements such as rare earths and precious metals.

Electrochemical techniques, including membrane electrolysis, are also showing potential in refining high-purity metals from low-concentration solutions. While these systems are commercially available, their broader adoption is hindered by scalability issues. However, their high selectivity makes them particularly effective in recovering dispersed critical minerals, ensuring that even trace elements can be extracted and reintegrated into supply chains.

Box 3.1 AI's potential to accelerate geological exploration and supply diversification

The Mingomba copper deposit in Zambia is one of the largest undeveloped copper deposits in the world. It is estimated to contain about 9 Mt of copper at a grade of 3.6%, around seven times that of the average copper mine. It was first discovered in the 1970s and planned as an extension to the Lubambe mine, located in the heart of the Zambian Copperbelt. Commercial copper mining in the region has been ongoing for more than a century, relying on its large, high-grade orebodies. Despite the resource potential indicated by the deposit's proximity to existing reserves and commercial operations, the depth of the orebody – about 1-2 kilometres underground – presented challenges in resource characterisation and recovery.

In 2022, KoBold Metals, a company specialising in AI-driven mineral exploration, acquired a stake in the Mingomba project and began applying its machine-learning and data-driven geoscience methodologies. In 2024, KoBold validated the conclusions of a 2020 concept study commissioned by Lubambe. Unlike conventional greenfield exploration, Mingomba provided a rich legacy dataset including seismic surveys and historic drill core logs which KoBold used to train its AI models.

Rather than relying on costly, high-density drilling, the AI model focused surveying efforts on areas that would yield the most useful data. This iterative process, comprising data acquisition, model refinement and expert decision-making, allowed geologists to improve resource estimates while minimising costs and environmental impact.

While KoBold's approach is cutting-edge, it is not the first time unconventional methods have disrupted mineral exploration. A notable precedent is the Goldcorp Challenge, launched in 2000 by Goldcorp Inc. Faced with an underperforming mine and uncertain geological targets, the company released proprietary geological data to the public, offering half a million dollars in prizes for the best analysis. Winning entries, including 3D models using remote data, identified over 110 drilling targets, over half of which were previously unknown. More than 80% of these yielded significant gold reserves, unlocking an estimated USD 6 billion in value.

The Goldcorp and KoBold case studies illustrate the ongoing technological advances in mineral exploration where AI and machine learning are augmenting geologists' decision-making. As high-grade, near-surface deposits are depleted, expanding and rapidly assessing the search space for mineral resources is essential for secure, affordable mineral supplies.

AI models trained on multimodal datasets that include geophysical, hyperspectral and drilling data can detect patterns imperceptible to traditional methods, improving the likelihood of success of both greenfield exploration and the reassessment of complex deposits. However, most models are currently trained on specific geologies using available data, limiting their ability to identify significant new resources in unexplored regions.

Beyond exploration, AI is also beginning to play a role in refining and processing, where it can optimise metallurgical workflows, reduce energy consumption and improve recovery rates. By analysing real-time sensor data from processing plants, AI systems can dynamically adjust parameters such as temperature, reagent dosage and grind size to maximise efficiency and reduce waste. In addition to lowering operational costs, it can also contribute to more responsible resource extraction.

	Exploration	Mine operation	Processing and metallurgy
Description	Enhanced resource discovery, assessment and characterisation	Enhanced automation and assessment of operations to improve efficiencies Remove human operation of haulage vehicles	Enhanced use of data from real-time processing operations to gain efficiencies
Examples	Geophysical data analysis, remote sensing, geochemical modelling, drill target optimisation	Predictive maintenance, fleet dispatch, ore grade control Autonomous haulage	Process automation, sensor-based sorting, machine vision in flotation, metallurgical modelling

Technological bottlenecks need to be addressed to build diversified midstream facilities, with targeted policies to shorten the path to commercialisation

Diversified midstream facilities for refining and processing are a key part of resilient critical mineral supply chains. Achieving this goal faces significant technological and cost bottlenecks that stem from gaps in processing expertise, environmental regulations, and capital and operating costs. Addressing these gaps requires innovation in extraction, refining and recycling technologies, alongside strategic investments in alternative processing methods, supply chain partnerships and policy frameworks that can accelerate the development of diversified midstream capabilities.

The recent export restrictions by China on LFP cathode production, rare earth separation and lithium refining technologies highlight the importance of technology in establishing geographically diverse refining and processing capabilities. Intellectual property bottlenecks present an additional challenge, limiting the transfer of knowledge and impeding the development of new refining capacities in other regions. Addressing these technology gaps is crucial, but equally important is the advancement of next-generation refining technologies that offer improvements in cost, energy efficiency and environmental performance. Developing and deploying such innovations is a long-term endeavour that requires sustained investment and integration with existing industrial infrastructure.

In the case of REEs, China has established a strong position in this sector, refining over 90% of the world's outputs. Lynas Rare Earths is investing in low-acid leaching techniques to separate REEs with reduced hazardous waste. Similarly, Ucore Rare Metals is pioneering RapidSX technology, an advanced continuous-flow solvent extraction system that increases processing rates.

For graphite, over 80% of global coated spherical graphite is produced in China, primarily using hydrofluoric acid-based chemical purification techniques that involve environmental impacts. Several companies are actively working on alternative purification methods with higher environmental performance. Syrah Resources is developing hydrofluoric acid-free purification methods, instead using thermal and alkaline-based chemical treatments to produce battery-grade graphite. Northern Graphite is focused on high-temperature graphitisation processes, eliminating the need for acid-based chemical purification while maintaining high purity levels. Although these technologies remain more costly than existing processes, further investment and refinement could bring costs down while meeting stricter environmental regulations.

Countries must take proactive steps to ensure that emerging technologies are not only developed but also successfully commercialised. While many promising technologies perform well in controlled environments or at pilot scales, transitioning to full-scale industrial deployment often faces technical, financial and regulatory hurdles. The ability of new technologies to reach commercialisation depends on many factors, but supportive policies and incentives have played a major role in the success of past breakthroughs. Government support can play a crucial role in bridging this gap by funding R&D efforts as well as pilot and demonstration projects that help validate these technologies at scale.

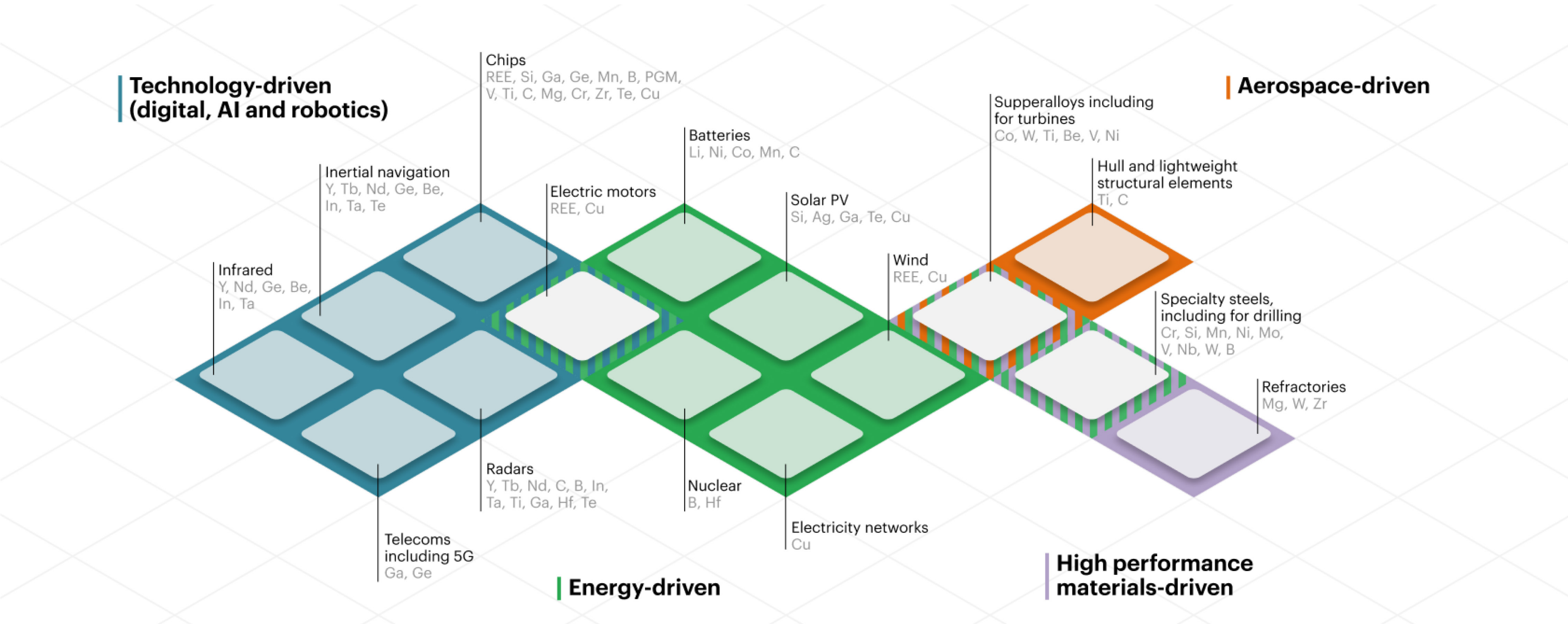
Several governments have recognised the importance of midstream innovation and are actively promoting it through funding programmes, regulatory incentives and strategic partnerships. The United States allocated substantial funding to domestic refining projects, particularly in lithium, rare earths and nickel sulphate production. Canada's Critical Minerals Research, Development and Demonstration Programme and the European Union's Horizon Europe initiative similarly aim to accelerate innovation in refining and processing capabilities.

Beyond domestic efforts, international collaboration on technology innovation is essential. Countries can leverage each other's strengths through strategic partnerships, technology-sharing agreements and co-investments in refining infrastructure. This approach not only enhances supply chain resilience but also fosters sustainable, environmentally responsible mineral processing practices worldwide. For example, the IEA's Technology Collaboration Programme supports global efforts towards scaling up novel technologies through its ability to convene different stakeholders for constructive dialogue and collaboration and its wide network of research and industry experts, which could be leveraged to support technology innovation for critical mineral supply chains.

Broader view on energy-related strategic minerals: What risks to anticipate?

Many energy-related minerals are used across multiple sectors, including digital technologies, aerospace and high-performance materials

Overview of broader energy-related strategic minerals



Notes: Excludes base metals such as aluminium, lead, tin and zinc. Ag = silver; B = boron; Be = beryllium; C = graphite; Co = cobalt; Cr = chromium; Cu = copper; Ga = gallium; Ge = germanium; Hf = hafnium; In = indium; Ir = iridium; Li = lithium; Mg = magnesium; Mn = manganese; Mo = molybdenum; Nb = niobium; Nd = neodymium; Ni = nickel; PGM = platinum-group metals; REE = rare earth elements; Sb = antimony; Si = silicon; Ta = tantalum; Tb = terbium; Ti = titanium; V = vanadium; W = tungsten; Y = yttrium; Zr = zirconium.

A broader perspective on energy-related strategic minerals is essential for both economic and energy security

The recent wave of technological advances in the energy sector has heightened the strategic importance of critical minerals such as copper, battery metals and rare earth elements. While their relevance is often associated with electrification, renewables and battery storage, their significance extends well beyond energy, underpinning a broad array of industrial and technological applications. From AI and robotics to high-performance materials and aerospace, these minerals are becoming increasingly central to industrial and technological development with broad economic implications.

At the same time, a wide range of other strategic materials also have significant implications for the energy sector. Even when their demand is driven mainly by other industries such as technology, aerospace and high-performance alloys, these materials have strong connections with energy systems. Developments in the technology sector, for example, can have major ripple effects on energy applications, and conversely, innovations within the energy sector can drive new demand for materials used in other industries.

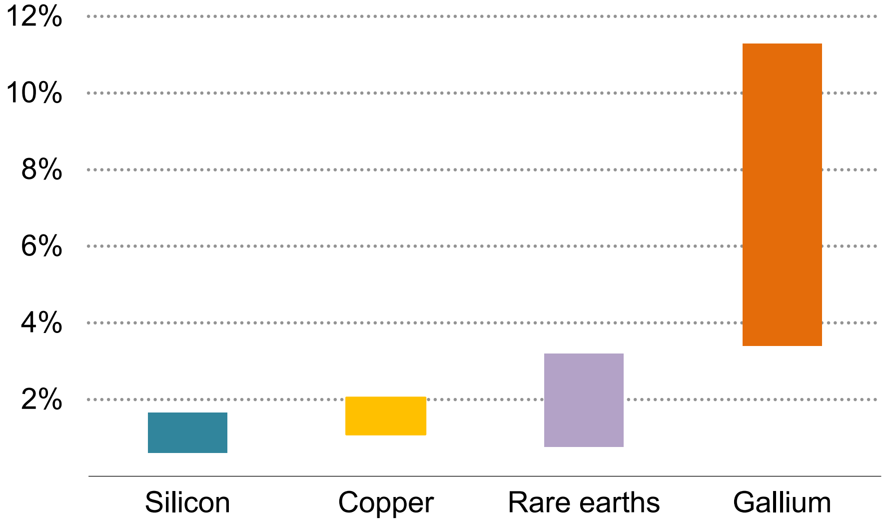
There are significant interlinkages among end uses. For example, chips are essential for many energy technologies. EVs rely on hundreds of logic and processing chips to function. AI is also becoming increasingly vital for optimising energy systems and improving efficiency. Not only do they have direct applications in energy, but the high-tech end uses they support are also critical for advancing energy innovation. For these reasons, this section explores the broad spectrum of energy-related minerals, in order to identify key risk factors that could hinder the development of both the energy sector and the broader economy.

Renewables have replaced digital technologies as the main consumer of various minerals; will AI reverse this?

Electronics and solar PV often rely on the same minerals and share interconnected supply chains. Materials essential to semiconductors such as high-purity silicon, indium, and those critical for optoelectronics, including germanium and gallium, are also key in solar PV production.

In the early 2000s, demand for high-purity silicon was largely driven by the rapid expansion of the digital economy, which accounted for three-quarters of total consumption. However, the widespread adoption of solar PV has since reshaped this dynamic, with 97% of the high-purity materials now directed towards solar PV and only 3% going to the digital sector. Gallium, indium, tantalum and REEs are additional examples of these interlinkages.

Demand for critical minerals required to meet the growth in data centre capacity in 2030 as a share of their total demand in 2024



Note: The bands for each mineral represent the estimated range of their demand from AI data centres in 2030 as a share of their total demand in 2024.
Source: IEA (2025), Energy and AI.

The future of these dynamics may well be more complicated with the rise of AI. Data centre capacity required to support the AI expansion could push up demand for these critical minerals. By 2030, data centres alone could push mineral consumption to notably higher levels, reaching up to 2% for copper, nearly 2% for silicon, over 3% for rare earth elements and a remarkable 11% for gallium. The electronics industry stands to benefit from its shared supply chain with the rapidly scaling solar PV sector and vice versa, reinforcing the interdependence of these two industries.

A similar trend for robotics and drones?

Developments in robotics, potentially accelerated by AI, may drive a similar trend. Magnet rare earth elements were once mostly used in hard drives and other electronics devices, but energy technologies such as EVs and wind power have emerged as a major consumer of these materials. However, as robotics and drones become more widely used, they could present an additional fast-growing source of demand for rare earth-based motors, which could create competition with the energy sector. Robotics also require a wide range of specialty minerals such as gallium, germanium, indium, tantalum and others, for radars, infrared and inertial navigation, which are also used in the energy sector, notably for solar PV.

Aerospace and critical mineral demand

The aerospace sector is another area where an intersection with the energy sector is strong, due to the use of superalloys. High-performance alloys designed to withstand very high temperatures and stresses are essential in both industries. Multiple families of superalloys exist, whether nickel-, cobalt- or iron-based alloys, each containing a wide range of additional input metals, including chromium, titanium, boron, zirconium, niobium, rhenium, tungsten, hafnium, molybdenum and tantalum.

Aerospace accounts for roughly two-thirds of the demand for these materials, primarily for aircraft engines, while the energy sector is also a major user of these materials, mainly for industrial turbines.

Although the aerospace sector consumes a relatively smaller mass of raw materials than other industries, the sector's demand for lightweight and high-performance materials makes it a key driver for multiple niche commodity markets. The sector consumes close to half of the world's titanium metal production, notably the high-grade TA6V alloy, which is a staple in aerospace manufacturing. It also plays a crucial role in the demand for chromium metal and samarium.

Risks and opportunities related to the role of defence applications in commodity markets

Defence applications generally account for a small fraction of total demand for critical minerals. Even for those minerals where military use is most pronounced, such as titanium and tungsten, the share of total consumption rarely exceeds 10%. Copper, a major mineral crucial to the energy system, also plays a crucial role in defence applications: while estimates vary from up to 2% in Europe, up to 5-7% in the United States, and some analysts estimate that defence uses may represent over 7% of total consumption.

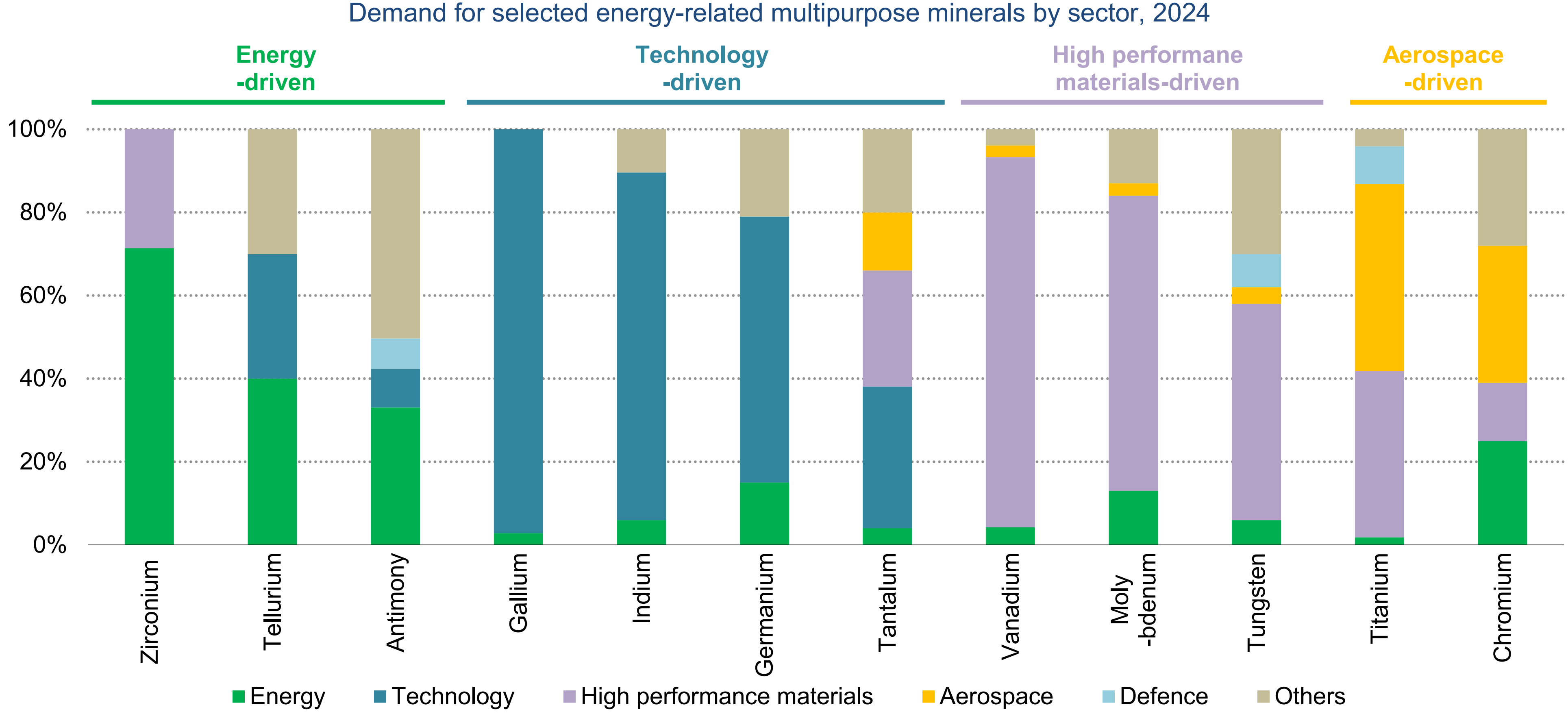
The defence sector's relatively small share of overall demand limits its influence on global markets and prices. However, a broad range of civilian technologies, including aircraft, land vehicles, digital infrastructure, robotics and power supply infrastructure, have some roles to play in defence applications. In practice, most commodities do have a small number of defence-related consumers. This presents both risks and opportunities for other industries.

One risk is the potential for newfound strategic concerns over military applications to disrupt the free flow of critical minerals. Recent export controls on minerals essential for clean energy and digital technologies have often been justified by their relevance to dual-use technologies, which serve both civilian and military purposes. However, the close link between defence and civilian industries also creates additional incentives for governments to monitor and secure mineral supply chains. These concerns have led to new investments aimed at protecting domestic mining and refining capabilities, including international collaborations, such as the United States' investments in Canadian tungsten, cobalt and graphite mines.

Scope of analysis

In this section, we cover 20 energy-related, multisectoral minerals to understand potential risk areas that could have major economic implications. These include key energy minerals discussed in Chapter 2 such as copper, lithium, nickel, cobalt, graphite, rare earths, manganese and silicon as well as other strategic minerals such as antimony, chromium, gallium, germanium, indium, molybdenum, tantalum, tellurium, titanium, tungsten, vanadium and zirconium. This section places more emphasis on the latter group of minerals, which have not been covered in other parts of the report. While base metals such as steel, aluminium, lead, tin and zinc are also vital to many end uses, the focus here is on those with smaller market sizes and limited trading liquidity, characteristics that make them more vulnerable to supply disruptions.

How are multisectoral strategic minerals used?



Note: Germanium, gallium, indium and tantalum are known to have some defence uses, but defence share is shown only when data are available.
Sources: IEA analysis based on BRGM, EC JRC, Fastmarkets, ICDA, ITIA, IWCC, JOGMEC, Louvigné, Roskill/Woodmac and USGS.

Many strategic mineral markets remain relatively small and opaque, making disruptions harder to detect, with far-reaching consequences on downstream consumers

Taken together, the energy, technology and other strategic sectors are increasingly becoming driving forces shaping critical mineral markets. The combined effect of rising demand across these sectors could result in rapid consumption growth, placing pressure on often small and fragile supply chains. Supply may struggle to keep up, particularly given the limited number of production facilities for many minerals, often extracted as by-products, and the high concentration of supply. Rigid supply structure, constrained by long development timelines and high capital costs, limits the system's responsiveness. This structural inflexibility makes markets particularly vulnerable to trade restrictions, amid growing geopolitical tensions. Despite their strategic importance, many of these markets remain relatively small and opaque, making disruptions harder to detect but potentially far-reaching in impact. Shortages could hinder manufacturing output, including in the energy sector, affecting availability, affordability, and employment. Sudden changes in the prices or availability of these minerals can then cascade through downstream sectors, driving up costs and hindering innovation.

A range of parameters can be used to assess the key risk factors facing these strategic multisectoral minerals. We adopted the below market indicators to understand potential risk areas.

- **Historical price volatility,** reflecting limitations in the ability of supply to respond to shifts in demand or market disruptions.

- **Supply concentration,** measured by the share of global output accounted for by the leading producing country, which can amplify geopolitical and market risks.

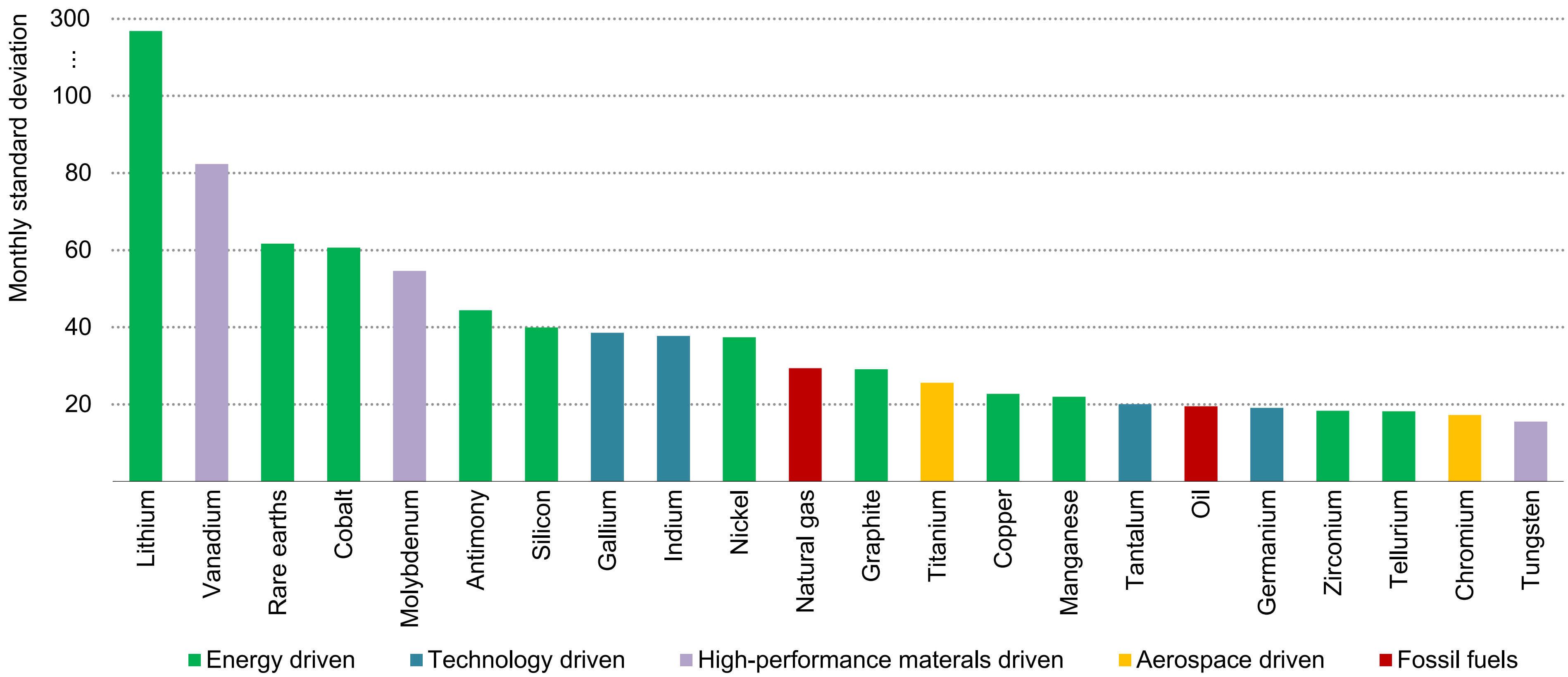
- **Ease of substitution,** assessing the extent to which a mineral can be replaced by another material or technology without significant performance or cost penalties. Low substitutability increases vulnerability to supply disruptions.

- **Co-product dependency,** where a mineral is primarily produced as a by-product of another commodity, making its supply less responsive to direct demand or price signals.

- **Trade restrictions,** including recent export bans, licensing requirements, or other barriers imposed by key supplier countries that can limit global availability and heighten supply risk.

Among 20 strategic minerals, 75% have shown greater price volatility than oil, and half have been more volatile than natural gas

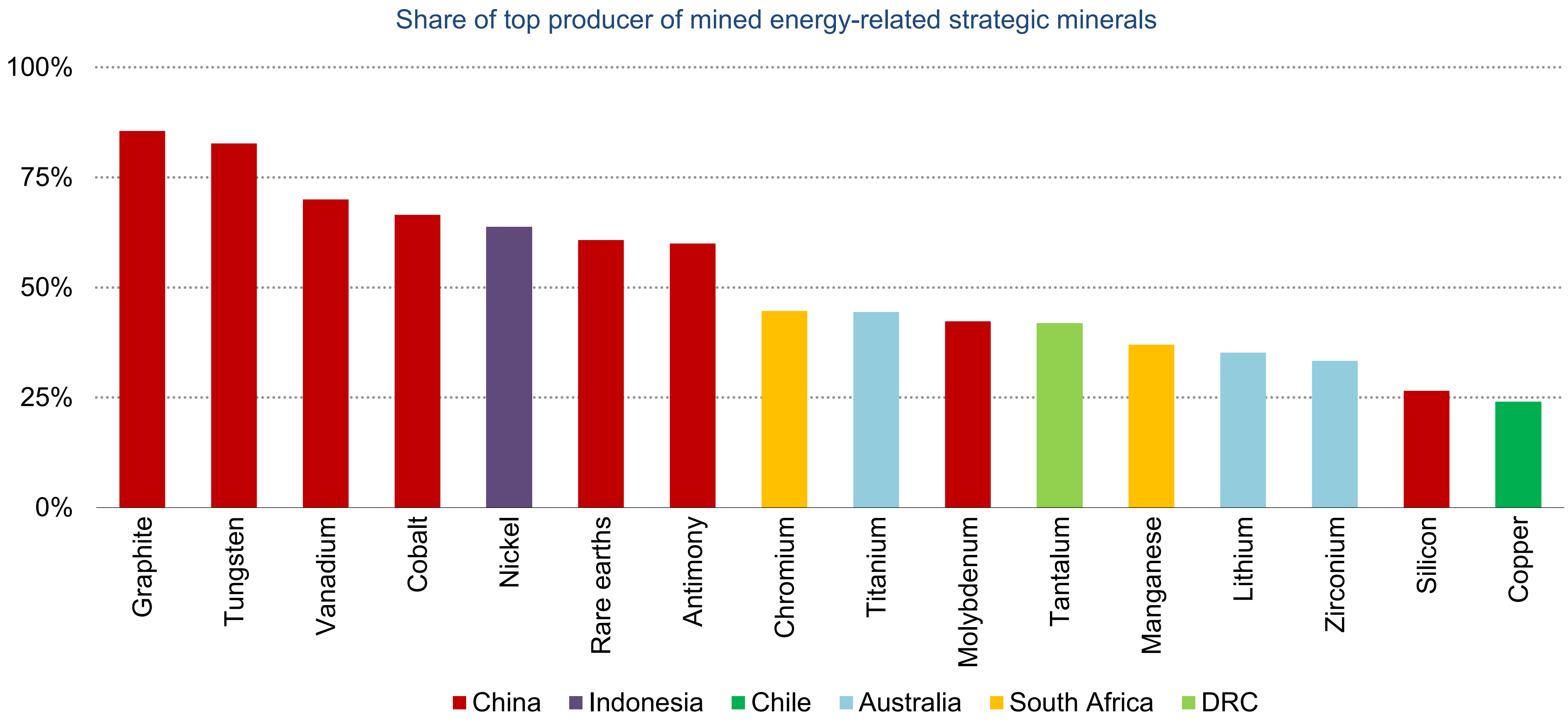
Monthly price volatility for selected minerals and fossil fuels, January 2014-March 2025



Note: Due to data availability, the volatility values for some minerals were calculated over differing time frames: January 2020 to March 2025 for graphite, January 2018 to March 2025 for manganese, March 2017 to March 2025 for titanium, and September 2019 to March 2025 for indium.

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

Over 40% of strategic minerals have a single top producer accounting for more than half of global production, highlighting significant supply concentration risks

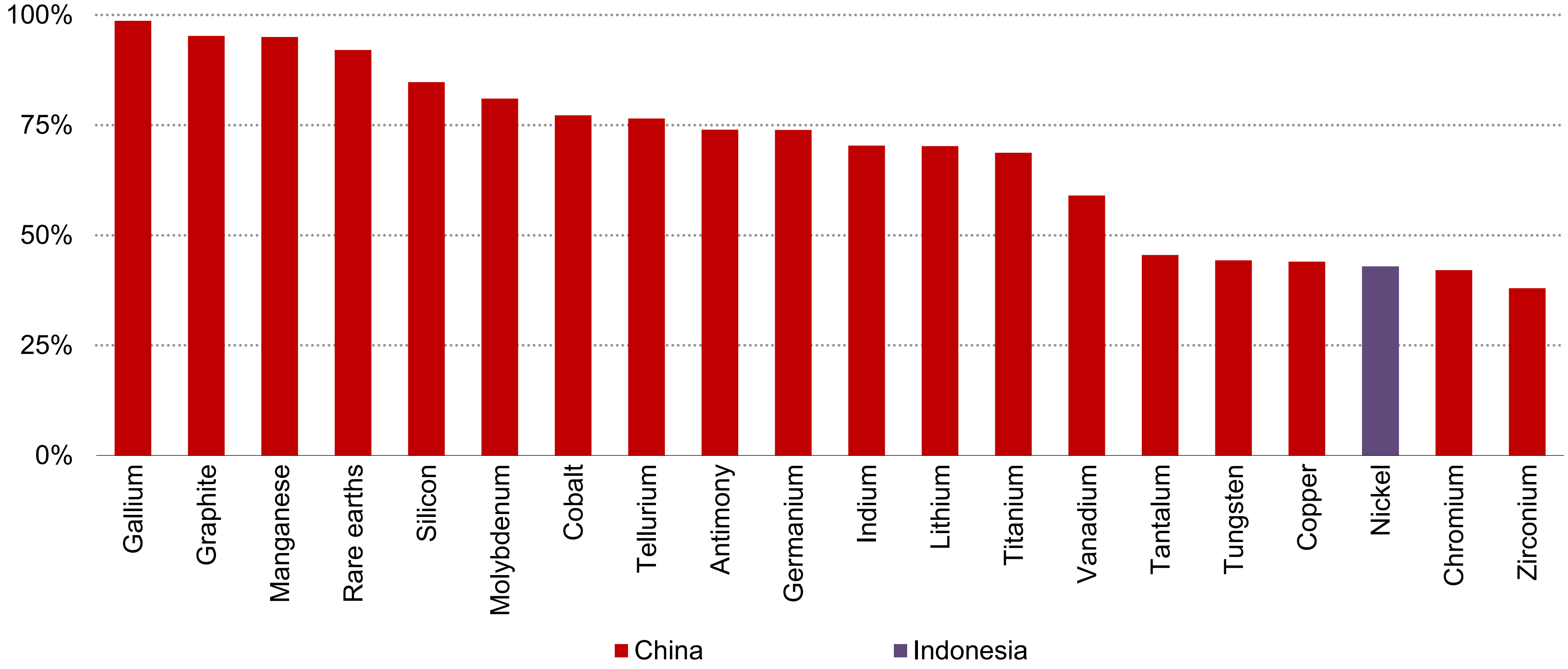


Notes: DRC = Democratic Republic of the Congo. Based on the most recent year for which data are available. The figure for silicon refers to silica mining. Gallium, germanium, indium and tellurium are not shown as they are almost entirely produced as a by-product.

Sources: IEA analysis based on USGS (2025), Mineral Commodity Summaries 2025, and EU Raw Materials Information System (accessed April 2025).

For refined material production, China is the leading producer for nearly all of the 20 minerals analysed and has an average market share of around 70%

Share of top producer of refined energy-related strategic minerals



Notes: Based on the most recent year for which data are available. The figure for titanium refers to titanium metal. The figure for manganese refers to high-purity manganese sulphate. The figure for molybdenum refers to ferromolybdenum.

Sources: IEA analysis based on USGS (2025), Mineral Commodity Summaries 2025, and EU Raw Materials Information System (accessed April 2025).

Substitution challenges create dependencies for strategic minerals that are hard to mitigate in the near term

Substitutability of selected strategic minerals in various applications

Function	Zirco-nium	Tellu-rium	Anti-mony	Gallium	Indium	Germa-nium	Tanta-lum	Vana-dium	Molyb-denum	Tung-sten	Titanium	Chro-mium
Electronics & photonics	◕	◔	◑	◔	◔	◔	◔	●	●	◑	◕	◕
Structural & mechanical	◔	◕	◕	●	●	●	◑	◔	◔	○	◔	○
Chemical, energy, catalytic	◔	◑	◑	◑	◕	◑	◔	◑	◑	◑	◑	◑
Other specialised applications	◕	●	●	◕	◕	●	◑	◕	◕	◑	◔	◑

Notes: Circles indicate the ease of substitution. ○: The mineral is very difficult or impossible to replace in key functions. Substitutes are likely to have significantly reduced performance and/or higher costs. ●: There is little demand for the mineral in this sector, or it is relatively easily substituted by other materials or technologies for main functions within this category, with readily available alternatives offering comparable performance at similar costs.

Electronics and photonics: Uses related to electronics (semiconductors, circuits, capacitors) and photonics (optics, radar, sensors).

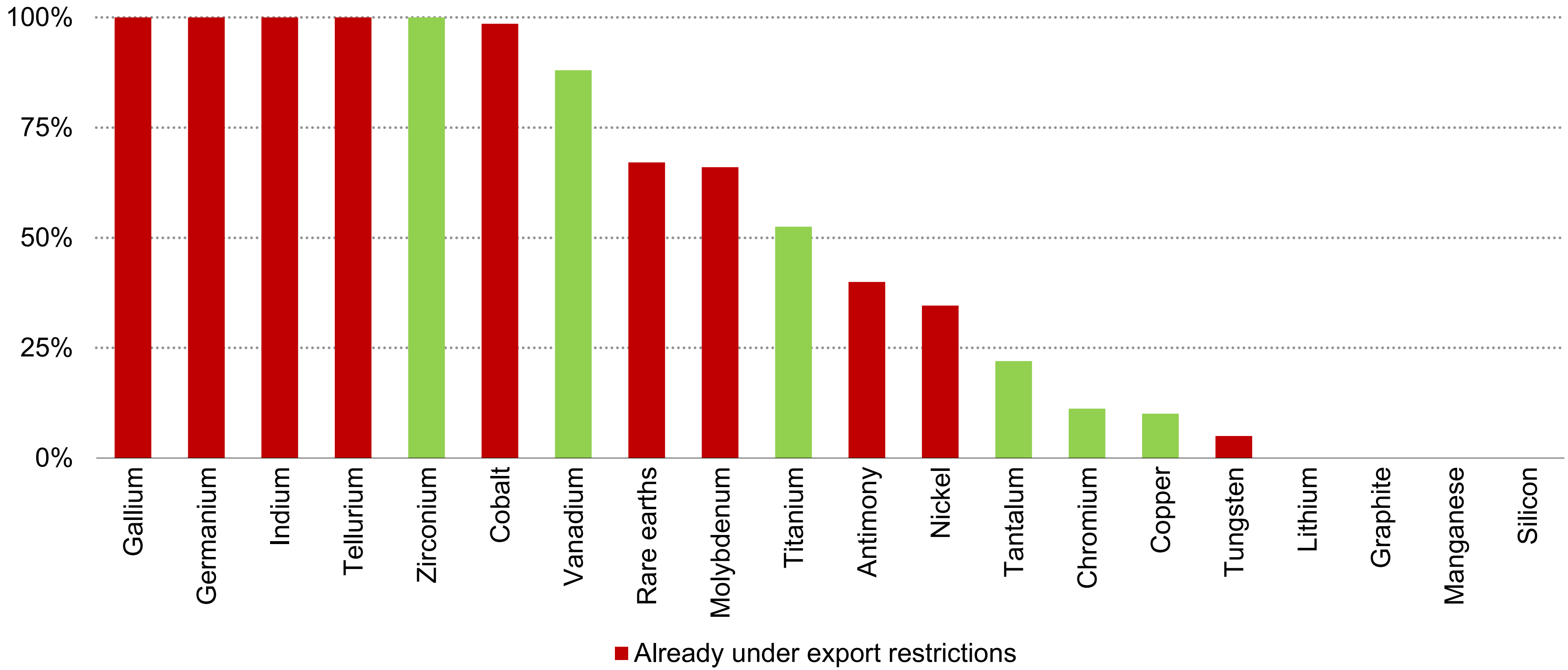
Structural and mechanical: Uses where the mineral is used to create desirable physical properties such as strength or stiffness in applications such as alloys or composites.

Chemical, energy, catalytic: Uses where the mineral acts as a catalyst, provides specific chemical properties (e.g. corrosion resistance), or plays a key functional role within energy conversion, storage or related systems (e.g. batteries, nuclear components).

Other specialised applications: Various uses not easily classified above, including specific optical (e.g. pigmentation) or tribological (e.g. lubrication) properties.

Around half of strategic minerals are produced as by-products, limiting the flexibility of their supply. Moreover, 55% of these minerals are already subject to some form of export restrictions, further compounding supply risks

Share of co-product or by-product production in total production for strategic minerals



Source: IEA analysis based on USGS (2025), Mineral Commodity Summaries; BGS (2025), UK 2024 Criticality Assessment.

High supply chain concentration, price volatility and by-product dependency amplify supply risks for strategic minerals

Price volatility is a defining feature of critical mineral markets. Disruptions and price fluctuations present significant challenges for downstream manufacturing sectors, with ripple effects across the broader economy. The volatility often stems from the relatively small size and limited transparency of these markets, where even modest changes in supply or demand can cause substantial price swings. Among 20 broader energy-related, multisectoral strategic minerals, 75% have historically exhibited greater price volatility than oil, and half have been more volatile than natural gas.

These risks are amplified by high levels of supply concentration, especially in refining and processing stages. Some 70% of refined strategic material outputs are dominated by a single top producer holding more than 50% market share, mostly China. For example, nearly all global production of refined gallium, battery-grade graphite, high-purity manganese and refined rare earths occurs in a single country. As a result, policy changes, supply disruptions or technical issues in these regions can have disproportionate global impacts.

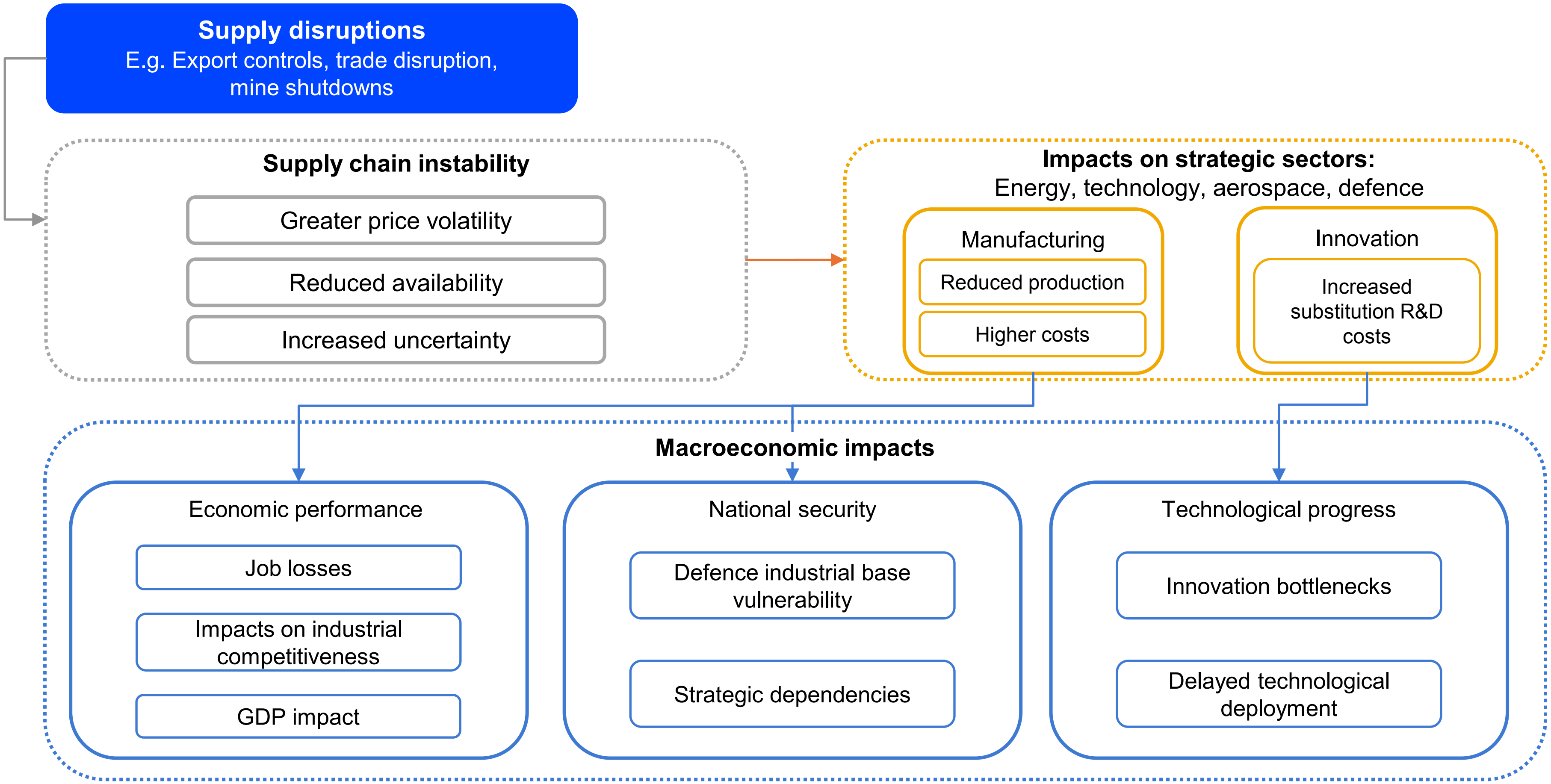
Substitution remains a major challenge. For many minerals, including tantalum, titanium and vanadium, viable alternatives are limited or involve major trade-offs in cost and performance. These dependencies may be difficult to overcome in the short term, underscoring the need for strategic planning to enhance resilience.

Trade restrictions increasingly affect critical mineral markets, with a recent wave of export control measures, particularly from China, adding to the uncertainty. These risks are heightened by the fact that many strategic minerals are produced not as stand-alone commodities, but as co-products or by-products of primary commodities. Minerals such as tellurium, gallium and germanium are typically recovered during the processing of copper, nickel or aluminium ores, meaning their supply is inherently tied to the output of these primary commodities rather than to their own market dynamics. This may create a disconnect between supply and demand: even as demand for a strategic mineral rises, supply may remain constrained if the primary metal is not experiencing similar growth. The result is limited responsiveness in supply to demand and price signals, amplifying the risk of shortages and price spikes.

However, this co-product nature also presents opportunities. Since these minerals already exist in mined ores, such as gallium or indium in zinc ores, or germanium in aluminium ores, boosting their output may not require new mining operations. Instead, expanding or upgrading refining and processing capacity could increase recovery rates from existing ore streams. If supported by the right incentives and technological capabilities, this pathway offers a more capital-efficient and faster route to easing supply constraints.

Supply disruptions can impact industrial performance as well as long-term innovation and technological leadership

Effects of critical mineral disruptions on strategic sectors and downstream industries



Critical mineral supply disruptions can have wide-ranging economic implications, but can be mitigated through holistic resource management strategies

The economic importance of these multisectoral strategic minerals extends far beyond their specific applications and creates deep interdependencies across the modern economy. Disruptions to their supply can have major economic consequences that impact manufacturing, innovation and national competitiveness.

Shortages or significant price spikes in these minerals pose an immediate threat to manufacturing output across a spectrum of high-value industries. This vulnerability is amplified by the inherent supply chain weaknesses, including high geographic concentration, reliance on opaque markets and co-product dependencies that limit supply responsiveness. The result is not just reduced production but also impacts on product availability and affordability, creating inflationary pressures and downstream bottlenecks for industries reliant on these manufactured goods.

Beyond immediate production impacts, unreliable access to strategic minerals can create significant bottlenecks for innovation. These materials are fundamental enablers for next-generation technologies such as electric vehicles, energy storage, artificial intelligence, advanced robotics, high-performance computing, specialised aerospace components and other energy breakthroughs. Material scarcity or prohibitive costs can slow R&D, delay the deployment of cutting-edge solutions, and ultimately hinder long-term technological developments that support economic growth. These direct effects on industrial output and innovation capacity influence long-term economic performance.

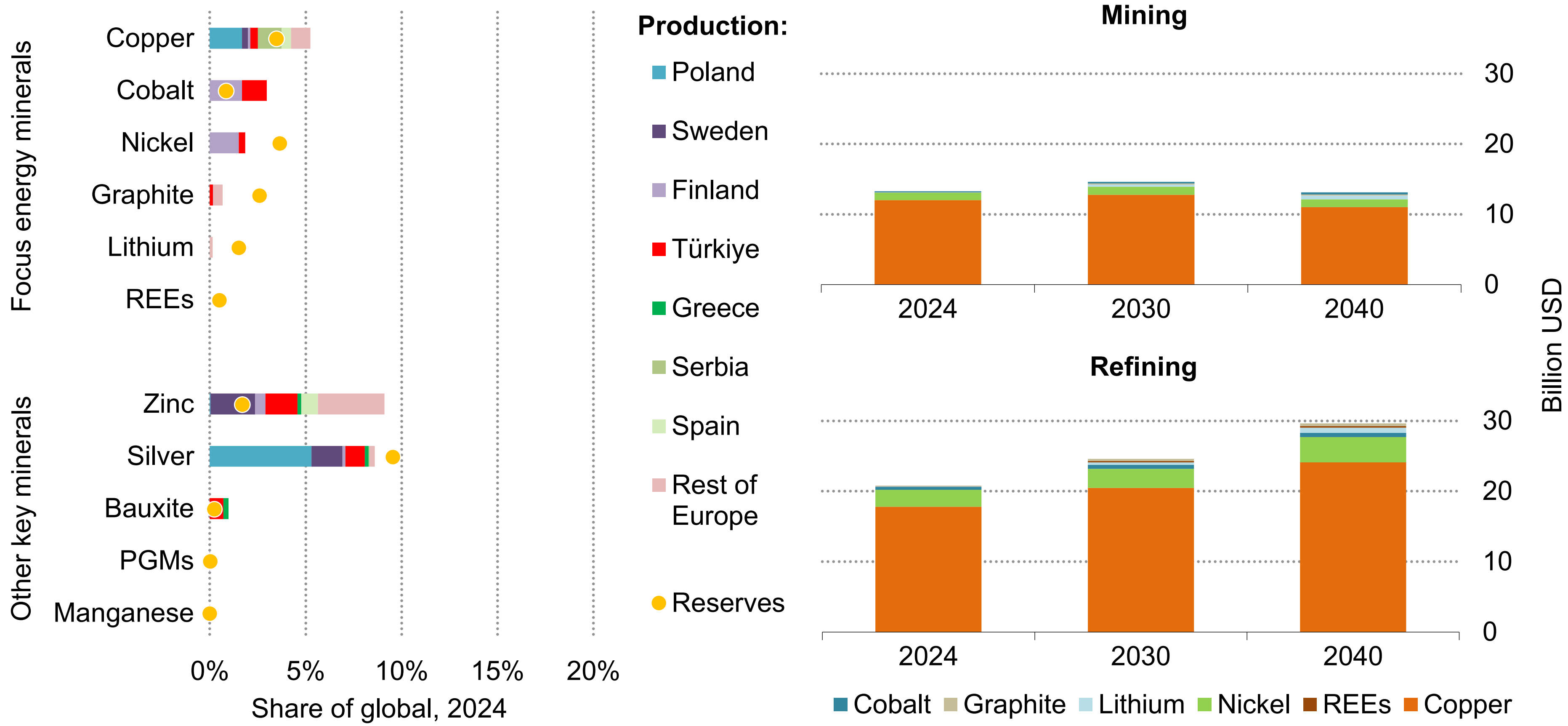
Furthermore, sustained cost pressures or diminished innovation capabilities relative to global peers can affect the long-term industrial competitiveness of an economy, potentially leading to shifts in global market share for high-value-added sectors reliant on these minerals. Such structural adjustments within industries are likely to have effects on employment.

Addressing these significant economic and strategic implications requires proactive policies aimed at mitigating critical mineral supply and price volatility. This can involve fostering greater supply chain transparency and mineral traceability, supporting recycling and technological innovation to manage demand and primary supply requirements, and incentivising diversification through financial support and market-based mechanisms. Such integrated strategies can build adaptable and secure supply chains capable of supporting national strategic objectives across energy and key industrial sectors.

4. Regional snapshot

Europe

Europe's share of global mined production and reserves in 2024 (left) and market value of key energy minerals (right)



Notes: REEs = rare earth elements; PGMs = platinum-group metals. The production figures are for magnet REE only and reserves figures for all REEs. Graphite refers to natural graphite.

Source: IEA analysis based on USGS (2025), Mineral commodity summaries and S&P Global (2025), European Commission (2025), RMIS - Raw materials' profiles.

Regulatory support and investments in Europe have ramped up to support critical mineral supply

Supply and investment snapshot

Europe is a significant player in silver, holding nearly 10% of global reserves and accounting for 9% of global production, primarily in Poland. The region also maintains a modest presence in copper, cobalt and nickel, accounting for 5%, 3% and 2% of global mining output (respectively). Future growth potential is contingent on further exploration, technological improvements and regulatory support such as the European Union (EU) Critical Raw Materials Act (CRMA).

The market value of Europe's key energy minerals production currently stands at approximately USD 13 billion for mining and USD 21 billion for refining in 2024, largely due to copper mining and refining. Announced projects indicate a growth in refining to USD 30 billion by 2040, primarily driven by copper and nickel refining. Europe represents about 8% of the global market value for refined materials by 2040, with growth driven by Belgium, Finland, Germany, Poland, Spain and Sweden.

Latest policy developments

European nations are continuing to deploy efforts to reduce import dependencies and mitigate supply chain vulnerabilities, including through increased domestic production and supply chain diversification. EU member states and the European Commission are continuing to implement the CRMA, which came into force in May 2024 and seeks to ensure that EU extraction, processing and recycling of strategic raw materials meet 10%, 40% and 25% of annual EU consumption by 2030 respectively. In March 2025, the European Commission reached an important milestone in CRMA implementation with the adoption of the first list of "strategic projects" on EU territory. Projects designated as "strategic" will benefit from streamlined permitting provisions, easier access to finance and institutional support to connect with relevant off-takers. A total of 47 projects across 13 EU member states have been selected, covering 14 raw materials and involving various segments of the value chain (from mining to processing and recycling). The European Commission could soon recognise additional projects located in non-European countries as "strategic" under the CRMA. In addition, the European Commission intends to create a joint purchasing platform for critical minerals in 2025 (based on the European Union's experience with natural gas purchasing) and is exploring the creation of raw material stockpiles. In the United Kingdom (UK), the government has announced that it will publish a new critical minerals strategy in 2025 to replace the previous one issued in 2022.

European nations are also stepping up funding for, and investment in, critical mineral projects. The European Commission and the European Bank for Reconstruction and Development launched a joint facility in July 2024 to provide equity investments for exploration activities, aiming to mobilise around EUR 100 million in investments. Later, in March 2025, the European Investment Bank adopted a new critical minerals initiative that includes an expected EUR 2 billion in funding and a dedicated one-stop shop for raw material projects. That same month, the European Commission released an Action Plan for the Automotive Industry, which includes a Battery Booster package. As part of this package, the European Commission will disburse EUR 1.8 billion to support companies manufacturing batteries and plans to introduce local content requirements for battery cells and electric vehicle (EV) components. Also announced as part of this package is the planned creation of a Battery Raw Materials Access Entity that will help car manufacturers obtain raw materials by pooling their investments.

At the national level, many governments are allocating funds for critical minerals projects, including through the establishment of national investment funds for raw material projects. In 2023, France established a public-private critical minerals investment fund, which includes EUR 500 million from the French government and seeks to raise an additional EUR 1.5 billion from private investors. In Germany, a EUR 1 billion raw materials fund has been created, managed by Germany's state-owned development bank. The Italian government has similarly announced the creation of a Made in Italy fund, consisting of EUR 1 billion in public funds. In the Netherlands, Invest International (the Dutch national investment entity) announced in March 2025 that it would launch a public-private investment fund to secure Dutch and European access to critical raw materials. In the United Kingdom, a GBP 15 million funding programme has been launched to support innovation in rare earth supply chains, while the National Wealth Fund has invested GBP 24 million in a domestic lithium project. The United Kingdom has also set up a GBP 850 million Automotive Transformation Fund to support the development of a domestic zero-emission vehicle supply chain, which has been used to provide funding for a rare earth separation project, a lithium refinery project, and a geothermal brine lithium project. European nations are also attracting investments from abroad: in March 2025, the Japan Organization for Metals and Energy Security (JOGMEC) and Iwatani announced a plan to invest EUR 110 million in a French rare earth refining project through a joint venture called Japan France Rare Earths.

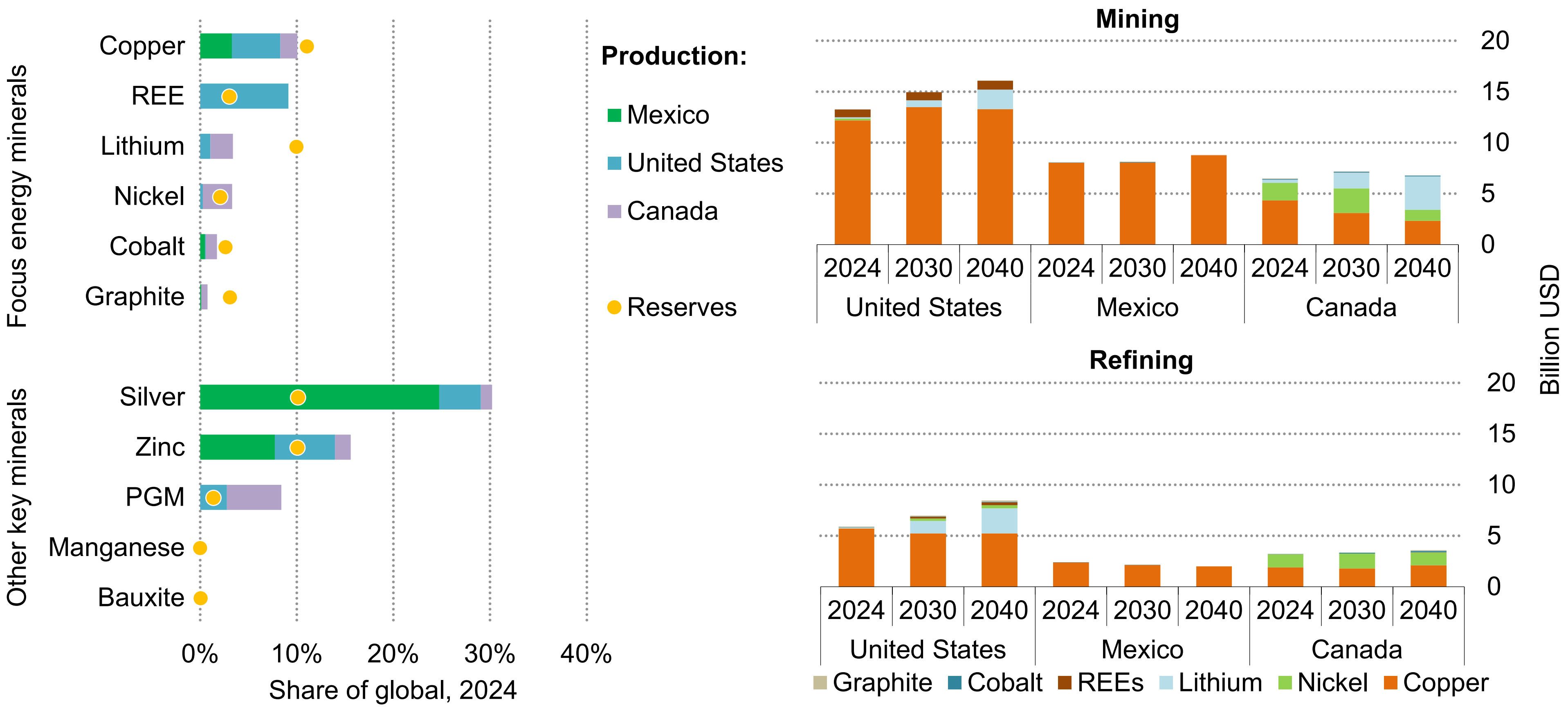
European nations are also engaging with countries outside Europe in an attempt to secure access to critical raw materials. France has signed 15 strategic mineral partnerships, while the United Kingdom has signed 9 of them. The European Commission has similarly signed raw material partnerships with 14 countries, and in January 2025 announced that it would begin negotiating new Clean Trade and Investment Partnerships, which will contain provisions on regulatory co-operation, trade and investment rules, and global investment.

European export credit agencies are also increasingly being called upon to provide financial support for overseas raw materials projects on which European importers rely. For example, in October 2024, UK Export Finance announced that it would provide financial support (in the form of credit guarantees) to overseas companies that supply critical minerals to UK companies, while Atradius DSB (the Dutch export credit agency) is currently piloting a loan guarantee facility for raw material projects that have economic significance for the Netherlands.

As regards sustainability policies, the European Commission proposed an omnibus simplification package in February 2025 that aims to streamline sustainability requirements, including those contained in the Corporate Sustainability Reporting Directive and the Corporate Sustainability Due Diligence Directive. Proposed changes include: narrowing the scope of covered entities; delaying the implementation of requirements by one to two years; reducing the frequency of monitoring exercises from annually to every five years; removing the requirement to put into effect a transition plan; eliminating the EU-wide civil liability regime; harmonising due diligence provisions; and limiting due diligence to direct suppliers. At the same time, in March 2025, the European Commission clarified a long-standing ambiguity and reclassified black mass as hazardous waste, thereby banning the export of black mass to non-member countries of the Organisation for Economic Co-operation and Development (OECD). As part of the Competitiveness Compass released in January 2025, the European Commission also announced its intention to introduce a Circular Economy Act in 2026 to promote greater recycling by EU industry.

North America

North America's share of global mined production and reserves in 2024 (left) and market value of key energy minerals (right)



Notes: REEs = rare earth elements; PGMs = platinum-group metals. The production figures are for magnet REE only and reserves figures for all REEs. Graphite refers to natural graphite.

Source: IEA analysis based on USGS (2025), Mineral commodity summaries and S&P Global (2025), European Commission (2025), RMIS - Raw materials' profiles.

Public support for domestic projects is increasing in Canada and the United States, together with greater efforts to diversify supply chains

Supply and investment snapshot

North America accounts for an important share of global reserves of various critical minerals. The United States (US) has significant reserves of lithium, copper and rare earths. Canada has substantial graphite, lithium and nickel reserves. Mexico possesses significant copper reserves. North America is also an important player in mining output, accounting for 10% of global copper output and 9% of global rare earth output. In 2024, the United States approved its first domestic lithium mine in over 60 years.

The market value of North America's key energy minerals production is projected to grow to around USD 30 billion for mining and USD 14 billion for refining by 2040, based on announced projects. For mining, this is largely driven by growth in copper mining in the United States and Mexico, as well as lithium and nickel mining in Canada. For refined materials, North America represents about 4% of the global market value by 2040, with growth driven largely by copper and lithium refining in the United States and copper and nickel refining in Canada.

Latest policy developments

Policy approaches to critical mineral projects differ among North American countries, with varying levels of government support shaping the development of projects across the region. In Canada and the United States, public support for domestic critical mineral projects is increasing. Both countries are providing financial incentives to stimulate private sector investment in domestic projects, such as the Advanced Manufacturing Production Credit in the United States and the Critical Mineral Exploration Investment Tax Credit in Canada. The US Department of Energy has provided loans to several domestic projects, including a USD 102 million loan for a graphite processing facility in Louisiana and a USD 700 million commitment for on-site processing of lithium at a mine in Nevada. Based on the Defense Production Act, the US Department of Defense (DOD) has provided awards to domestic projects, including USD 90 million for a lithium mine in North Carolina and USD 35 million for a rare earth processing facility in California. In January 2025, the US Export-Import Bank (EXIM) launched a new financing tool, called the Supply Chain Resiliency Initiative, to provide targeted financing for critical mineral projects that supply US companies. In March 2025, the US President issued an Executive Order ordering the DOD and the US International Development

Finance Corporation (DFC) to establish a fund for investments in domestic critical mineral production. Canada has rolled out several funding programmes to support the expansion of its critical mineral sector, including the establishment of a CAD 1.5 billion (Canadian dollars) Critical Minerals Infrastructure Fund and the allocation of CAD 1.5 billion under the Strategic Innovation Fund for critical mineral projects.

In 2024, Canada and the United States also began providing joint support for projects of strategic importance to both nations. In May 2024, the two countries also announced a joint investment in two Canadian critical mineral projects (one located in Quebec and the other in the Northwest Territories). Later, in December 2024, the two countries announced another co-investment in a project located in Yukon. Canada and the United States have also provided support for a cobalt refinery project in Ontario.

Canada and the United States are also deploying efforts to expedite project development. The United States has allocated USD 350 million to its Permitting Council to improve environmental review processes and USD 40 million to the Environmental Protection Agency to hire and train additional permitting staff. Several bills have also been introduced in the US Congress to facilitate and accelerate project development, including the Energy Permitting Reform Act of 2024. In January 2025, the US President issued an Executive Order declaring a national energy emergency and directing relevant government agencies to use emergency authorities to facilitate and expedite the development of domestic energy resource projects, including critical mineral projects. In a separate Executive Order issued the same day, the US President directed relevant government agencies to identify regulations and actions that impose a burden on domestic mining and processing projects, undertake efforts to eliminate permitting delays and accelerate geological mapping of domestic resources. In Canada, the federal government released a plan in June 2024 to modernise and improve federal permitting processes.

Both countries are combining public support for domestic projects with the implementation of trade measures intended to diversify supply chains. In May 2024, the United States increased import tariffs on several Chinese products, including critical minerals, batteries, EVs, solar cells and semiconductors. Canada followed suit in October 2024 by imposing a 100% import surtax on Chinese-made EVs and announcing consultations concerning potential tariffs on batteries, semiconductors, solar products and critical minerals. In February 2025, the United States launched an investigation into whether US reliance on copper imports affects US national security. This was followed by the launch of a similar investigation in April 2025 focusing on imports of processed critical minerals and derivative products. Both of these investigations could lead to the imposition of tariffs or other trade restrictions by the United States. While the United States announced a raft of tariffs in April against many of its largest trading partners, the United States has so far chosen to exempt strategic goods from these measures, including critical minerals and semiconductors. However, the global tariff landscape remains highly fluid, with potential tariff increases or decreases during the remainder of the year.

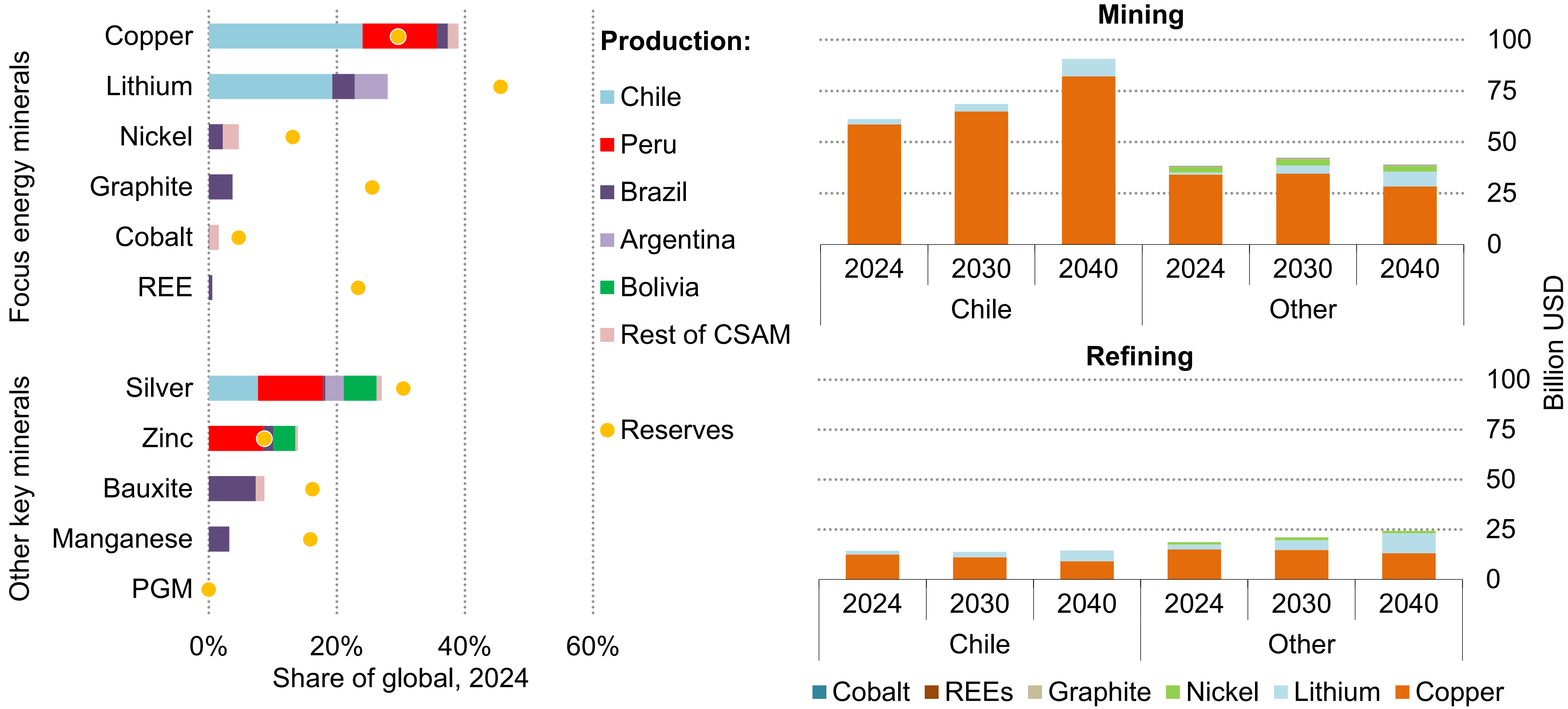
Meanwhile, both Canada and the United States are engaging with mineral-producing and mineral-consuming countries across the world. In 2022, the United States, Canada and other partners launched the Minerals Security Partnership, a multilateral initiative that aims to accelerate the development of diverse and sustainable critical mineral supply chains through targeted diplomatic and financial support for projects located across the world. Canada has signed bilateral critical mineral partnerships with ten countries plus the European Union, while the United States has signed arrangements with Argentina, India, Japan, Mongolia, Norway, Ukraine and Uzbekistan. As of April 2025, the United States was reportedly negotiating a critical mineral partnership with the Democratic Republic of the Congo (DRC). The United States is also investing in non-domestic projects through the DFC and EXIM, including a USD 50 million investment in a rare earth processing project in South Africa and a USD 150 million loan for a graphite project in Mozambique. In March 2025, the US President directed EXIM to deploy financing tools to secure US offtake of critical minerals in foreign countries for domestic processing.

Government support for mineral projects remains more unclear in Mexico. After Mexico nationalised its lithium sector in 2022, the country passed sweeping reforms to its mining regulatory framework in 2023, including limiting mining concessions to 30 years (down from 50); simplifying public expropriation of mining assets; limiting the scope of mining concessions to one mineral; facilitating permit cancellations; and limiting geological exploration to the Mexican Geological Survey. However, the new Mexican administration has expressed greater support for critical mineral projects (in particular lithium and copper projects to support EV production) and has announced a review of the previous administration's proposed ban on open-pit mining.

In terms of sustainability policies, Canada is continuing to pursue initiatives intended to render mining activities more sustainable, including the development of an inventory of mine tailings with critical mineral potential and the issuance of a new regulation in Ontario to facilitate the recovery of residual metals and minerals from mine waste. In the United States, the Securities and Exchange Commission paused the adoption of its 2024 climate-related disclosure rules pending completion of litigation, while a bill has been introduced in Congress to prohibit certain US companies from complying with foreign sustainability due diligence requirements (including EU ones).

Central and South America

Central and South America's share of global mined production and reserves in 2024 (left) and market value of key energy minerals (right)



IEA. CC BY 4.0

Notes: REEs = rare earth elements; PGMs = platinum-group metals; CSAM = Central and South America. The production figures are for magnet REE only and reserves figures for all REEs. Graphite refers to natural graphite.

Source: IEA analysis based on USGS (2025), Mineral commodity summaries and S&P Global (2025), European Commission (2025), RMIS - Raw materials' profiles.

Central and South America is a key region for the global critical minerals market, with vast reserves and a well-established mining sector

Supply and investment snapshot

Central and South America are rich in critical minerals such as lithium, copper, graphite, rare earths, nickel, manganese, silver and bauxite, led by countries such as Argentina, Bolivia, Brazil, Chile and Peru. The region holds approximately 45% of global reserves for lithium and 30% for copper. With a well-established mining sector, production has grown steadily, with the region contributing 40% of global copper output and 30% of lithium production.

Chile is a major producer of copper, responsible for 24% of global production. Additionally, the Salar de Atacama project in the country has been a significant source of lithium for years. Brazil, home to the Carajás Mine (one of the world's largest iron ore mines also producing nickel and copper), has rapidly emerged as a key player in critical mineral developments. The country's "Lithium Valley" in the state of Minas Gerais hosts 11 projects. Brazil also holds major untapped potential for graphite, nickel, manganese and rare earth elements. Argentina is also rapidly expanding its lithium production with supportive investment schemes.

Sizeable resources in the region are attracting investment from other regions and companies across the globe. Recent acquisitions include BHP and Lundin Mining's joint purchase of Filo Corporation for copper projects in Argentina and Chile, and Rio Tinto's acquisition of Arcadium Lithium (Argentina). Brazil is also emerging as a key destination for investment in the critical minerals sector. Brazil's Vale announced in February 2025 a major expansion of its mining operations at the Carajas complex in the north, planning to invest USD 12.2 billion through 2030 to enhance both iron ore and copper production. Rare earth elements in Brazil are also attracting investment, with the Minerals Security Partnership backing Serra Verde's project, highlighting the growing importance of diversifying supply chains. Chinese investments in the country have also been strategic, with BYD securing lithium mining rights, along with announcing a complex in Bahia that will manufacture EVs and process lithium and iron phosphate.

The market value of Central and South America's key energy minerals production currently stands at approximately USD 100 billion for mining and USD 19 billion for refining in 2024, with projections indicating growth to USD 130 billion and USD 24 billion respectively by 2040. For mining, the growth is primarily driven by copper mining in Chile and Peru. For refined materials, announced projects indicate that the region is set to represent about 7% of the global market value by 2040, with growth driven largely by copper and lithium refining in Chile, Argentina and Brazil.

Latest policy developments

Argentina's mining sector benefits from a liberal legal and regulatory environment through its Mining Investment Law and Large Investment Incentive Regime (RIGI) offering significant incentives, such as foreign exchange exemptions and zero tax on imported capital goods. The RIGI further guarantees fiscal stability for 30 years. However, limited information exists on investor uptake, and the country needs to carefully manage potential economic and political stability risks that may deter cautious investors.

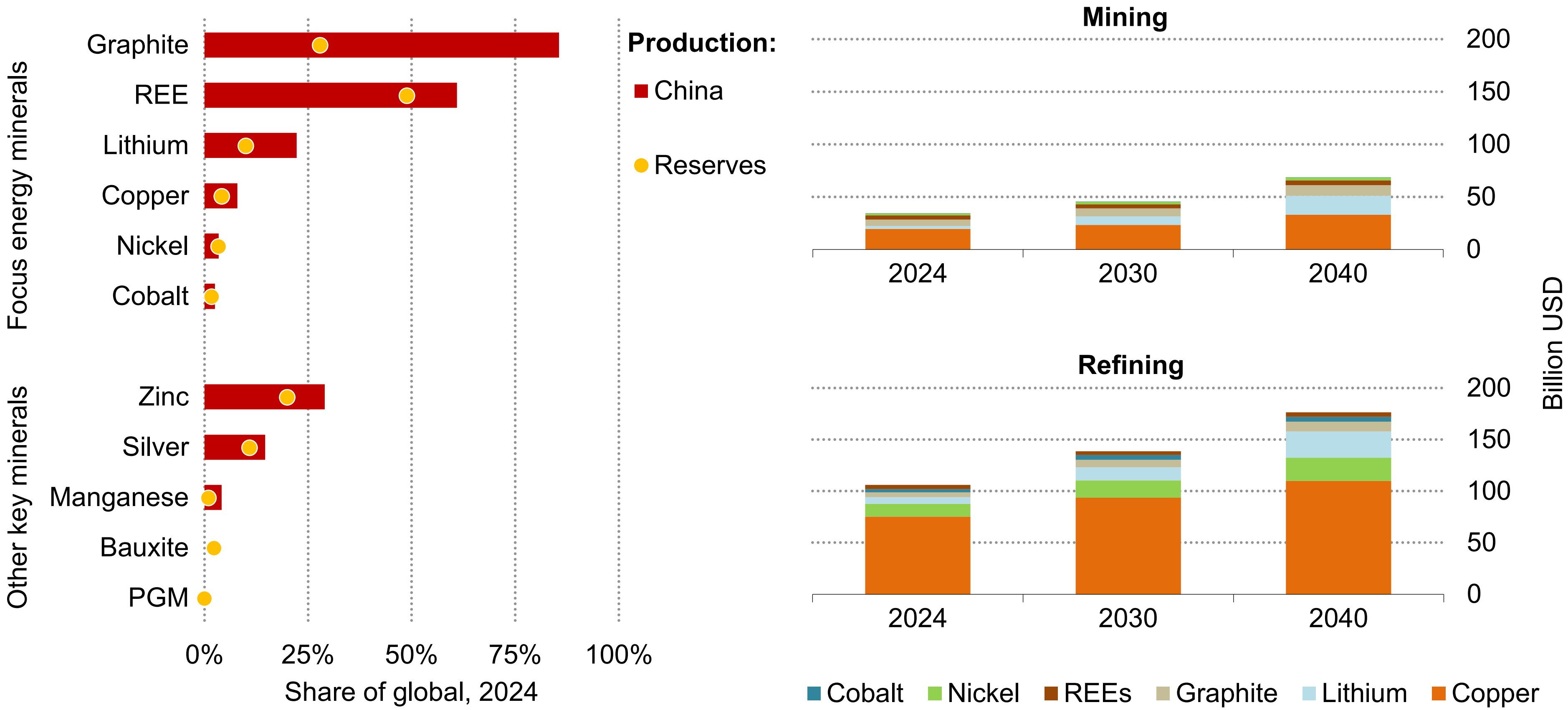
The Bolivian government has signed contractual agreements with companies from the Russian Federation (hereafter, "Russia") and China for lithium production, but is facing a setback as of March 2025 because of significant public opposition. The agreement with Russia, signed in December 2023, involves a USD 450 million investment by state-run Uranium One Group to build a pilot lithium plant in the Salar de Uyuni. The agreement with China, signed in November 2024, involves a USD 1 billion investment by Hong Kong CBC Investment Limited to construct two industrial plants in the Salar de Uyuni.

Brazil's National Bank for Economic and Social Development (NBESD) has launched initiatives promoting strategic minerals, including a BRL 5 billion public notice with the Brazilian Financing Agency for Studies and Projects to support the development of lithium, rare earth, nickel, graphite and silicon chains, mobilising investments for the manufacture of cells and magnets, as well as a private equity investment fund with Vale, with BRL 100 million to BRL 250 million in financing from NBESD. The Inter-Ministerial Committee for Strategic Mineral Projects has approved 19 projects worth USD 12 billion, demonstrating Brazil's commitment to developing its critical minerals sector through co-ordinated policy action.

Following the National Mining Policy 2050 in 2022, Chile announced its National Lithium Strategy in 2023. In December 2023, Chile passed a bill amending its mining regulatory framework – marking the first time the framework has been revised since 1983. These amendments address various aspects of mining operations, including mining concessions, mining fees and land rights disputes. In January 2024, the Chilean government introduced a bill in Chile's National Congress to create an Intelligent Permitting System. The system aims to streamline the permit process for mining projects, reducing processing times for major projects by 30%. By reducing bureaucratic hurdles, the government hopes to attract more foreign and domestic investment into the mining sector, while maintaining environmental standards.

China

China's share of global mined production and reserves in 2024 (left) and market value of key energy minerals (right)



Notes: REEs = rare earth elements; PGMs = platinum-group metals. The production figures are for magnet REE only and reserves figures for all REEs. Graphite refers to natural graphite.

Source: IEA analysis based on USGS (2025), Mineral commodity summaries and S&P Global (2025), European Commission (2025), RMIS - Raw materials' profiles.

China seeks to solidify its dominance in the critical minerals market through substantial strategic investments, increased control of supply and trade control measures

Supply and investment snapshot

China plays a dominant role in the global supply of critical minerals, for mining and more prominently for processing and refining. China holds important reserves of many critical minerals, accounting for 10% of global lithium reserves, 28% for graphite, 49% for rare earth elements (REEs) and 20% for zinc. China also accounts for a significant share of global mining output for many critical minerals, including 22% for lithium, 61% for REEs and 87% for natural graphite. Its influence is even stronger in refining, with a 44% share of global copper refining, a 70-75% share of lithium and cobalt processing, and a more than 90% share of REE and battery-grade graphite refining.

While China is the world's largest metallurgical transformation hub, it relies on imports for large volumes of raw materials, often from a small number of sources. For example, China relies heavily on the Democratic Republic of the Congo for its cobalt refining facilities. To secure supplies of raw materials, China is actively investing in mines abroad through Chinese state-owned enterprises with political support from the government. These investments are often structured through joint ventures and special purpose companies. Of sectors that received Chinese financing and investment support under China's Belt and Road Initiative (BRI), mining was the second-largest sector, receiving 18% (USD 21.4 billion) of investment in 2024. Engagement has been strong in Africa, Latin America and Indonesia. Zijin Mining Group Ltd., which holds a copper mine in the Democratic Republic of the Congo as well as the Tres Quebradas lithium project in Argentina, was the third-largest of all Chinese BRI investors in 2023. In 2024, JCHX Mining Management acquired 80% of the Lubambe Copper Mine in Zambia, the second-largest copper producing nation in Africa.

While foreign investment in the mineral sector is generally restricted, China also has a Positive List, the 2022 version of which encourages foreign investment in the development and application of new technologies to improve the utilisation rate for mine tailings and in the application of mine ecological restoration technologies. The Positive List also encourages foreign investment in the exploration, mining and beneficiation of mineral resources that are in short supply in China, such as potash and chromite.

The market value of China's key energy minerals production currently stands at approximately USD 35 billion for mining and USD 106 billion for refining in 2024, with announced projects indicating major growth to USD 68 billion and USD 176 billion respectively by 2040. For refined materials, China represents 50% of the global market value by 2040, up from 45% in 2024.

Latest policy developments

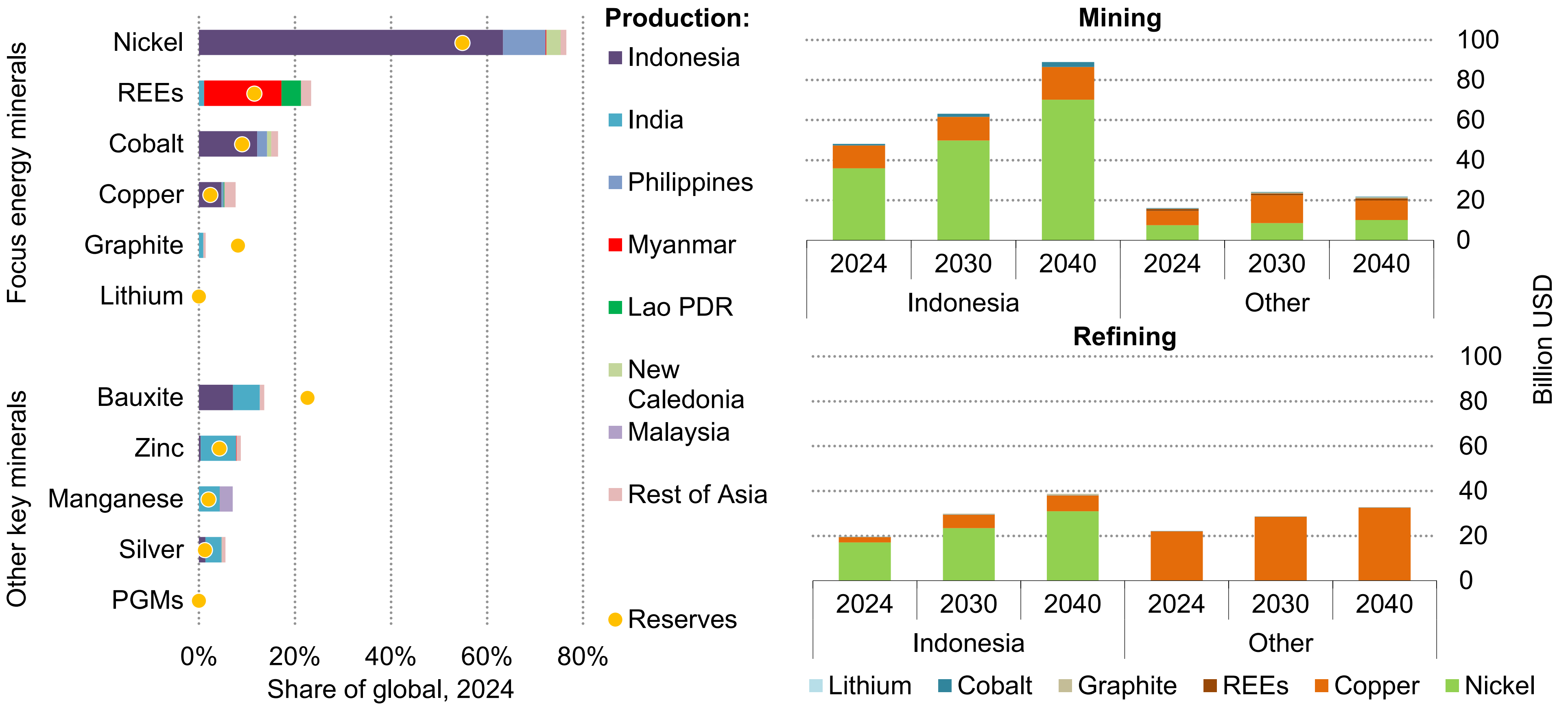
China has intensified its strategic export controls on critical minerals as part of its broader geopolitical strategy. In December 2024, China announced that it would ban exports of gallium, germanium and antimony (key materials for semiconductor production) to the United States, while simultaneously implementing stricter review procedures for graphite exports to the United States based on intended end use. In February 2025, China announced additional export controls on tungsten, tellurium, bismuth, indium and molybdenum. Later, in April 2025, China announced the implementation (with immediate effect) of export controls on seven medium and heavy REE-related items (samarium, gadolinium, terbium, dysprosium, lutetium, scandium and yttrium).

China is also deploying measures to enhance control over its domestic REE supply. In June 2024, China's State Council issued the Rare Earth Management Regulations, which came into force on 1 October 2024. The new regulations, which emphasise state ownership of REE resources, establish several provisions regarding the development, exploitation and use of rare earth resources in China, including a new "rare earth product traceability system" and a new quota system for rare earth mining and smelting. Later, in February 2025, China's Ministry of Industry and Information Technology (MIIT) released two draft regulations for public comment, with the consultation period ending on 21 March 2025. The two regulations are intended to further implement the State Council's Rare Earth Management Regulations. The first draft regulation concerns traceability, requiring covered enterprises to establish an enterprise-level system to track and record the flow of rare earth products. In parallel, the MIIT must set up a government-level traceability system, and covered enterprises must register onto the government-level traceability system and upload the required information. The second draft regulation concerns production quotas and stipulates that the MIIT will designate which enterprises are authorised to engage in rare earth mining and smelting. The MIIT will issue annual "indicators" to each authorised enterprise, including production quotas.

In addition, China has significantly ramped up its state funding for geological exploration, allocating more than CNY 100 billion (USD 14 billion) annually since 2022. This marks the highest three-year period of funding in a decade. Additionally, at least half of China's 34 provincial-level governments, including major resource-producing regions such as Xinjiang, have announced increased subsidies or expanded access for mineral exploration. Under China's Mineral Resources Law (revised in 2024), farmland can be expropriated to develop strategic mineral resources. To support the domestic mining sector, China provides subsidies, tax incentives and other forms of support, independent of commodities market cycles. These actions reflect China's strategic focus on securing access to critical minerals to enhance industrial and supply chain security amid global competition.

Asia (excluding China)

Asia's (excluding China) share of global mined production and reserves in 2024 (left) and market value of key energy minerals (right)



Notes: REEs = rare earth elements; PGMs = platinum-group metals; Lao PDR = Lao People's Democratic Republic. The production figures are for magnet REE only and reserves figures for all REEs. Graphite refers to natural graphite.

Source: IEA analysis based on USGS (2025), Mineral commodity summaries and S&P Global (2025), European Commission (2025), RMIS - Raw materials' profiles.

Asia has marked potential for an integrated supply chain, with complementary regional strengths and strategic policy frameworks

Supply and investment snapshot

Asia is integral to global critical mineral supply chains, with distinct strengths across subregions in extraction, processing and manufacturing. Asia (excluding China) holds significant reserves of several critical minerals, including 55% of global nickel, 12% of REEs, 9% of cobalt and 8% of graphite.

Southeast Asia is emerging as an important player in global critical mineral supply chains. Indonesia and the Philippines currently account for approximately 72% of global nickel output and 14% of global cobalt output. Indonesia is ramping up capacity by building new nickel smelters and boosting cobalt production. Myanmar ranks as the second-largest REE producer in the world (after China). India also possesses major untapped resource potential. In March 2025, the country launched an auction of exploration licences covering 13 mineral exploration blocks, including for copper, REEs and zinc.

Meanwhile, Japan and Korea have developed refining industries despite minimal domestic mining. Together, the two countries hold approximately 8% of global copper refining capacity, with Japan's processing capabilities for copper estimated at 1.5 million tonnes. Korea imports approximately 95% of its critical mineral demand, with both nations securing supply through strategic overseas investments.

By 2040, Southeast Asia's mining market value is projected to reach USD 110 billion, with refined materials at USD 70 billion. Japan and Korea's refined minerals market could reach USD 20 billion, driven primarily by copper and nickel refining. With extraction in Southeast Asia, potential resource development in India, and advanced processing in Japan and Korea, the Asia region has potential to become a regional critical minerals hub, supporting downstream manufacturing industries in the region and outside of it.

Latest policy developments

Across Asia, governments are implementing policies to develop and secure critical mineral supply chains, with Japan and Korea focusing on overseas investment and recycling initiatives, Southeast Asian nations emphasising domestic processing and value addition, and India planning to develop its untapped resources.

In Southeast Asia, the regulatory landscape is characterised by increasing state intervention and industrial policy. Governments throughout the region are prioritising value addition and downstreaming strategies, often through mechanisms such as export restrictions, with particular emphasis on developing integrated EV ecosystems. Recent legislative developments include Indonesia's 2020 amendments to its mining law for the purpose of introducing export bans and tax incentives to develop domestic supply chains. Regional co-operation has also been strengthened, including through the 2023 Declaration on Developing Regional Electric Vehicle Ecosystem among member states of the Association of Southeast Asian Nations (ASEAN), which focuses on collaborative development of regional supply chains.

Looking ahead, Indonesia's proposed amendments to its mining law in 2025 seek to broaden eligibility for mining rights, prioritise access to mining areas for entities that intend to establish domestic processing facilities, and favour domestic use of minerals over exports. Separately, in March 2025, Indonesia announced plans to increase royalties on mineral ores by replacing its current flat-rate system with a progressive rate system. For nickel ore, royalties would increase from 10% under the current flat-rate system to between 14% and 19% under the progressive system (depending on the price benchmark set by the Indonesian government). Indonesia also issued a regulation in February 2025 that requires foreign exchange earnings from natural resources (including minerals) to be kept within the domestic financial system for 12 months. Following Indonesia's example of promoting domestic processing, the Philippines is in the final stages of passing legislation to ban nickel exports within five years from enactment, while actively seeking foreign investment to develop its own downstream capabilities.

In Central Asia, Kazakhstan is a rising partner for consumer nations. The country has active strategic partnerships with Korea and the European Union. In March 2025, Kazakhstan awarded Canadian company Condor Energies a 6 800 hectare licence for solid minerals. These partnerships aim to enhance critical mineral supplies from both existing production and new greenfield sites, diversify supply chains, and bolster the development of essential minerals such as lithium and REEs.

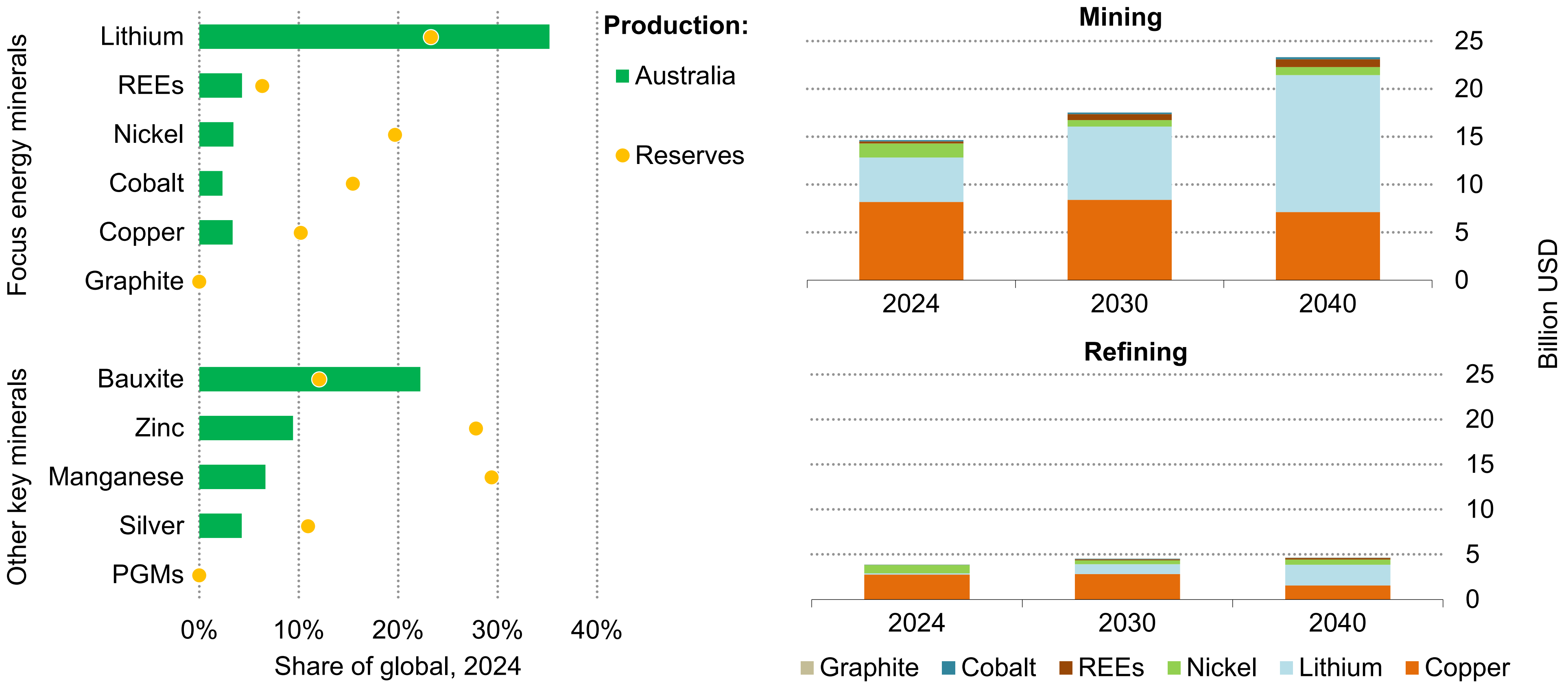
To develop its resources, India has launched the National Critical Mineral Mission (NCMM), designed to secure the supply of critical minerals and strengthen the country's critical mineral value chains. The NCMM encompasses mineral exploration, recycling, stockpiling, research and governance, with ambitious targets such as completing 1 200 domestic exploration projects and recovering 400 kilotonnes of recycled material. The government has demonstrated substantial financial commitment by earmarking INR 163 billion (Indian rupees) (USD 1.9 billion) for expenditure and expecting an additional INR 180 billion (USD 2.1 billion) investment from public sector undertakings. Additionally, the NCMM aims to promote research, achieve self-sufficiency in critical mineral processing and generate 1 000 patents across the critical mineral value chains by 2031.

In Japan, comprehensive financial support mechanisms have been established for critical mineral projects. JOGMEC is continuing to provide loans, debt guarantees and equity investments for various projects. In addition, in 2022, a total of JPY 105.8 billion (USD 0.7 billion) was allocated for critical mineral projects under the Economic Security Promotion Act, including around JPY 100 billion in subsidies. Pursuant to this subsidy programme, the Japanese government approved five projects on battery minerals and uranium totalling approximately JPY 31 billion in 2023 and 2024, including pilot projects to recover and refine nickel, cobalt and lithium from black mass. In addition to these subsidies, the Japanese government has allocated funds for equity financing of mineral projects, including JPY 159.7 billion mainly for copper. In an effort to bridge French and Japanese supply chains, JOGMEC and Iwatani announced in March 2025 plans to invest up to EUR 110 million in a French REE project (specifically for terbium and dysprosium) through a joint venture called Japan France Rare Earths, aiming to meet approximately 20% of Japan's future demand. In February 2025, Japan announced the Seventh Strategic Energy Plan, which sets out the basic direction of energy policy, noting that critical minerals are indispensable for responding to the expected increase in electricity demand. The plan places emphasis on ensuring stable supply through stockpiles, diversified supply sources and deep-sea mineral resources.

Korea has similarly strengthened its policy framework for critical minerals, reintroducing the investment tax credit system for overseas resource development in 2024 to promote company investment in critical minerals. Looking ahead, the government plans to establish a KRW 50 billion (Korean won) (USD 35 million) annual Supply Chain Stabilisation Fund to encourage public-private joint investment in critical mineral projects. Korea established the Critical Minerals Strategy in 2023 to enhance crisis response capabilities by building an early warning system, while also promoting stockpile expansion, resource co-operation and recycling. Building on this foundation, in 2023, the government announced policies that include enacting legislation to foster the battery recycling industry, establishing a battery life-cycle management system and introducing a certification system for recycled materials. Most recently, in March 2025, the Korean government announced a comprehensive plan to promote the reutilisation of critical minerals by establishing a domestic industry for used batteries and printed circuit boards. This initiative aims to produce essential minerals such as nickel, cobalt and lithium, with a goal to achieve a 20% recycling rate for ten strategic minerals by 2030, supported by creating industrial clusters, stabilising raw material supply chains and enhancing regulatory frameworks.

Australia

Australia's share of global mined production and reserves in 2024 (left) and market value of mining and refining (right)



Notes: REEs = rare earth elements; PGMs = platinum-group metals. The production figures are for magnet REE only and reserves figures for all REEs. Graphite refers to natural graphite.

Source: IEA analysis based on USGS (2025), Mineral commodity summaries and S&P Global (2025), European Commission (2025), RMIS - Raw materials' profiles.

Australia is a major player in global critical mineral supply chains, strategically deploying finance to build domestic supply chains and promoting strong sustainability practices

Supply and investment snapshot

Australia is a major player in global critical mineral supply chains, particularly for lithium and bauxite. The country holds the second-largest reserves of lithium in the world, accounting for approximately 23% of global reserves and 35% of global lithium output. The country's mineral resources are primarily concentrated in Western Australia, home to the Greenbushes lithium mine (one of the world's largest lithium mines) as well as the Mount Weld mine (a key source of REEs for years).

Investment in Australia's critical minerals sector is characterised by growing capital flows, with AUD 760 million newly invested in mineral exploration in 2023. The investment landscape is composed of both domestic and foreign capital, focusing primarily on lithium and REEs. The REE sector has attracted large capital investments in recent years. Key projects under development include Iluka Resources' Eneabba project (17.5 kilotonnes per year), Australia's first fully integrated REE refinery which is expected to commence production in 2027. Also significant is the National Reconstruction Fund Corporation's AUD 200 million commitment to Arafura Rare Earths Limited's Nolans Project in the Northern Territory. Market volatility presents challenges, as evidenced by the closure of three Western Australian nickel mines in January 2024 due to global oversupply and low prices.

The market value of Australia's key energy minerals production currently stands at approximately USD 15 billion for mining and USD 4 billion for refining in 2024, with announced projects indicating growth to USD 23 billion and USD 5 billion respectively by 2040.

Latest policy developments

The regulatory landscape for critical minerals in Australia is characterised by robust financial support mechanisms and stringent environmental, social and governance (ESG) practices. Australia provides substantial funding through Export Finance Australia, the Northern Australia Infrastructure Facility and the Clean Energy Finance Corporation, offering loans, guarantees and equity investments to develop critical minerals projects.

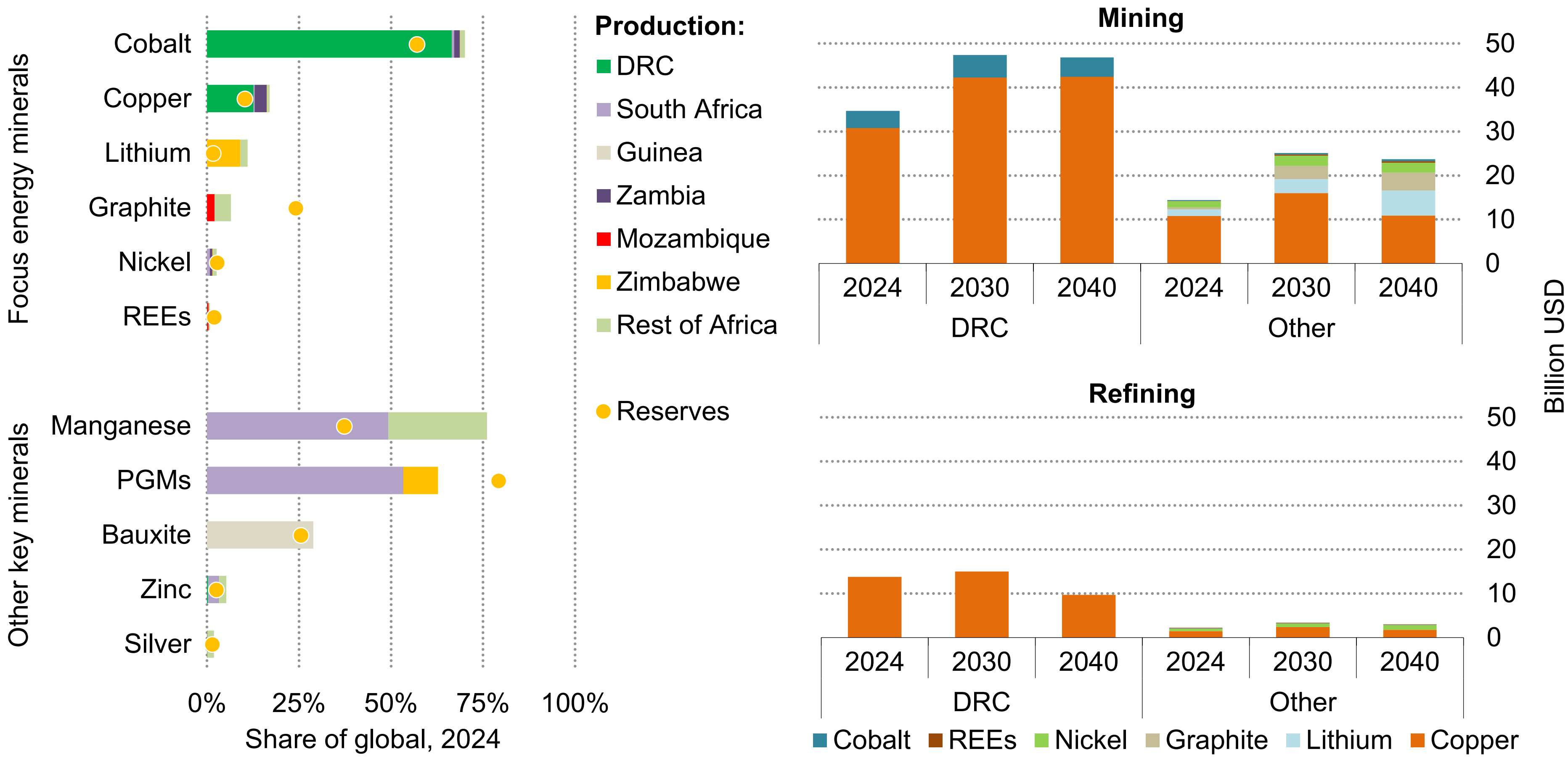
The Critical Minerals Strategy 2023-2030 presents a vision to position Australia as a world leader in ESG performance. Regulatory frameworks prioritise fast yet durable environmental approvals. These frameworks embed strong ESG practices into mining operations, which could potentially enable Australian access to premium markets, support the sector's enduring social licence to operate and ensure fair benefit-sharing with communities, including Aboriginal communities.

Recent legislative developments include the Future Made in Australia Act 2025, which establishes significant tax incentives specifically targeting investments in low-emissions hydrogen and critical minerals processing. Government strategies prioritise lithium, REEs and other battery minerals through the National Battery Strategy. A Critical Minerals Research and Development Hub was launched to address technical barriers along the value chain and support collaborative research projects, including by enhancing processing capabilities for lower-grade REE deposits.

Looking ahead, anticipated policy developments include further refinement of the Future Made in Australia Plan, focusing on domestic manufacturing using critical minerals. The overall policy direction indicates a comprehensive approach combining financial support, sustainability requirements and community engagement, which industry stakeholders view as supportive for long-term sector development while maintaining Australia's reputation for high ESG standards.

Africa

Africa's share of global mined production and reserves in 2024 (left) and market value of key energy minerals (right)



Notes: REEs = rare earth elements; PGMs = platinum-group metals; DRC = Democratic Republic of the Congo. The production figures are for magnet REE only and reserves figures for all REEs. Graphite refers to natural graphite.

Source: IEA analysis based on USGS (2025), Mineral commodity summaries and S&P Global (2025), European Commission (2025), RMIS - Raw materials' profiles.

Africa seeks to leverage its resources to maximise economic benefits, enhance bilateral co-operation and advocate transparency in critical mineral supply chains

Supply and investment snapshot

The African continent is home to vast resources of minerals that are critical for various energy technologies. Africa holds significant reserves of cobalt, graphite, manganese, bauxite and platinum. The Democratic Republic of the Congo currently accounts for around 70% of global mined cobalt production, while Africa as a whole currently accounts for 11% of lithium output and 17% of copper output. South Africa dominates global supplies of platinum-group metals and is also a leading producer of chromium and manganese. Most African countries export critical minerals primarily in their raw form. Developing local processing industries could boost profits, increase tax revenues, create higher-skilled jobs and enhance positive technological spillovers. Unlocking this potential, however, requires concerted efforts to address several challenges such as ensuring reliable and affordable electricity provision, strengthening transportation infrastructure, nurturing technical skills, and building regulatory capacity, among others.

The African continent is continuing to see growing investments, particularly from actors in the Middle East and China. In March 2025, a new lithium processing plant was nearing completion in Zimbabwe to process around 500 tonnes of ore per day, a project led by Chinese investors. Saudi Arabia and the United Arab Emirates are also investing in projects in the region, including in port infrastructure.

The market value of Africa's key energy minerals production currently stands at approximately USD 50 billion for mining and USD 16 billion for refining in 2024, with announced projects indicating overall growth to almost USD 83 billion by 2040. For mining, this is primarily driven by growth in copper and cobalt mining in the Democratic Republic of the Congo, but growth in the lithium market occurs in Zimbabwe, as well as in Madagascar and Mozambique for graphite. For refined materials, announced projects suggest that Africa may represent about 4% of the global market value by 2040, with growth driven largely by copper refining in the Democratic Republic of the Congo and by nickel refining in South Africa and Madagascar.

Latest policy developments

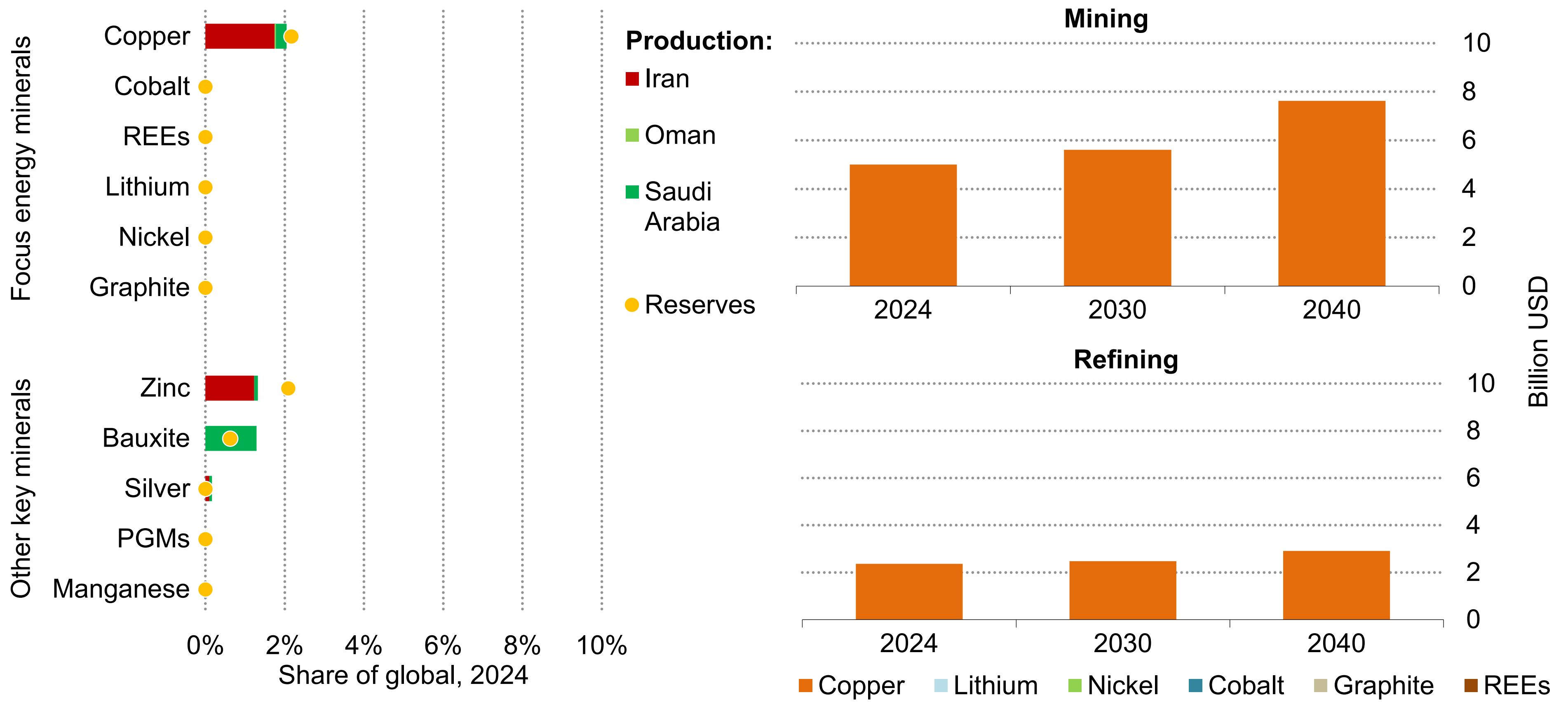
African nations are increasingly focusing on policies that would ensure value addition for their mineral resources, aiming to maximise domestic economic benefits from their vast mineral reserves. The Democratic Republic of the Congo has taken steps in this direction by temporarily banning cobalt exports in early 2025 to curb oversupply and stabilise global prices, part of a broader strategy to enhance domestic processing capabilities. The Democratic Republic of the Congo has also been reviewing whether to place export quotas and limits on production or shipments. In addition, the country has sought to formalise a partnership with the United States to obtain security assistance and secure its mining operations from conflict, for which negotiations are still in early stages.

Similarly, and following the introduction of export controls in 2022, Zimbabwe enacted the Base Minerals Export Control Order in 2023. The order introduces stringent controls on lithium mining, processing and exportation to promote domestic beneficiation and value addition. The government aims to stimulate local processing capabilities and attract investment in processing facilities, potentially increasing economic gains from its significant lithium reserves. Recent amendments to Zimbabwe's tax regime further support these efforts by introducing levies and taxes on mineral sales and transfers, encouraging compliance and transparency.

Improving transparency has also been a trend in the region: the Democratic Republic of the Congo is exerting pressure on the International Conference of the Great Lakes Region to enforce stricter mineral tracing standards to guard against illegal mineral exports; Zimbabwe expanded its definitions of "beneficial owner" and "controller" to guard against corruption; and Zambia introduced digital platform ZIMIS (Zambia Integrated Mining Information System) to enhance transparency in managing mining licences.

Middle East

Middle East's share of global mined production and reserves in 2024 (left) and market value of key energy minerals (right)



Notes: REEs = rare earth elements; PGMs = platinum-group metals. The production figures are for magnet REE only and reserves figures for all REEs. Graphite refers to natural graphite.

Source: IEA analysis based on USGS (2025), Mineral commodity summaries and S&P Global (2025), European Commission (2025), RMIS - Raw materials' profiles.

Middle Eastern economies see mineral commodities as a strategic pillar in economic diversification and are deploying longer-term capital across the value chain

Supply and investment snapshot

The Middle East region is currently not a significant producer of key energy minerals. Iran and Saudi Arabia produce modest amounts of copper, zinc and bauxite, but production of other minerals is virtually non-existent. Despite this, mineral exploration is ramping up, with production potentially increasing in the coming years. Saudi Arabia has claimed the existence of significant deposits of lithium, REEs, gold, zinc and copper, though most projects are still in the pre-exploration phase. Production capacity is developing, with lithium in particular rising as a focus for Saudi Arabia. In January 2025, Saudi Aramco and Ma'aden announced a USD 2 billion joint venture for extracting lithium and advancing direct lithium extraction (DLE) technologies, with commercial lithium production potentially starting in 2027. Efforts to produce lithium align with the country's Vision 2030 to diversify its economy. Additionally, in late 2024, Oman's Mazoon Mining announced that it had broken ground at its Mazoon Copper Project. Additional exploration activities are underway in Oman.

Although domestic exploration of lithium, copper and REEs is expanding, Middle Eastern countries are currently more focused on securing international offtake agreements and developing processing capabilities, rather than on becoming major raw material producers themselves. In line with these objectives, planned and announced investments in critical minerals projects by Middle Eastern actors total more than USD 20 billion, with Saudi Arabia and the United Arab Emirates leading this drive.

The investment landscape is dominated by state capital, with state-owned mining companies and sovereign wealth funds taking equity stakes in mining projects globally. Capital allocation has increased strategically, with investments directed towards securing positions across the entire value chain. The United Arab Emirates, for example, is investing heavily in refining, battery materials and circular economy initiatives. The country is also investing in ports across Africa and Latin America.

Announced projects in the region indicate that the market value of the Middle East's key energy minerals production is set to increase to USD 7.5 billion for mining and USD 3 billion for refining by 2040. For mining, the growth is primarily driven by growth in copper mining in Iran, but Saudi Arabia and Oman also see growth. For refined materials, the future market value could change with additional project developments.

Latest policy developments

The regulatory landscape for critical minerals in the Middle East is characterised by strategic positioning across global supply chains, through direct investment and international partnerships, with particular emphasis on processing capabilities and trade networks.

In Saudi Arabia, the government has allocated USD 182 million to provide incentives for mineral exploration. Moreover, the Future Minerals Forum established by the Saudi Arabia Ministry of Industry and Mineral Resources in 2021 to support the country's Vision 2030 objectives led to several strategic announcements for the country in January 2025 including a joint venture between Saudi Aramco and Ma'aden to explore critical minerals essential for the energy transition.

International co-operation frameworks are also increasingly common for regional actors. The United Arab Emirates has concluded significant mineral partnerships, including a USD 1.9 billion partnership with the Democratic Republic of the Congo and an investment partnership with Kenya of up to USD 500 million. Qatar's sovereign wealth fund has committed USD 180 million to TechMet, an investment vehicle supported by the US DFC.

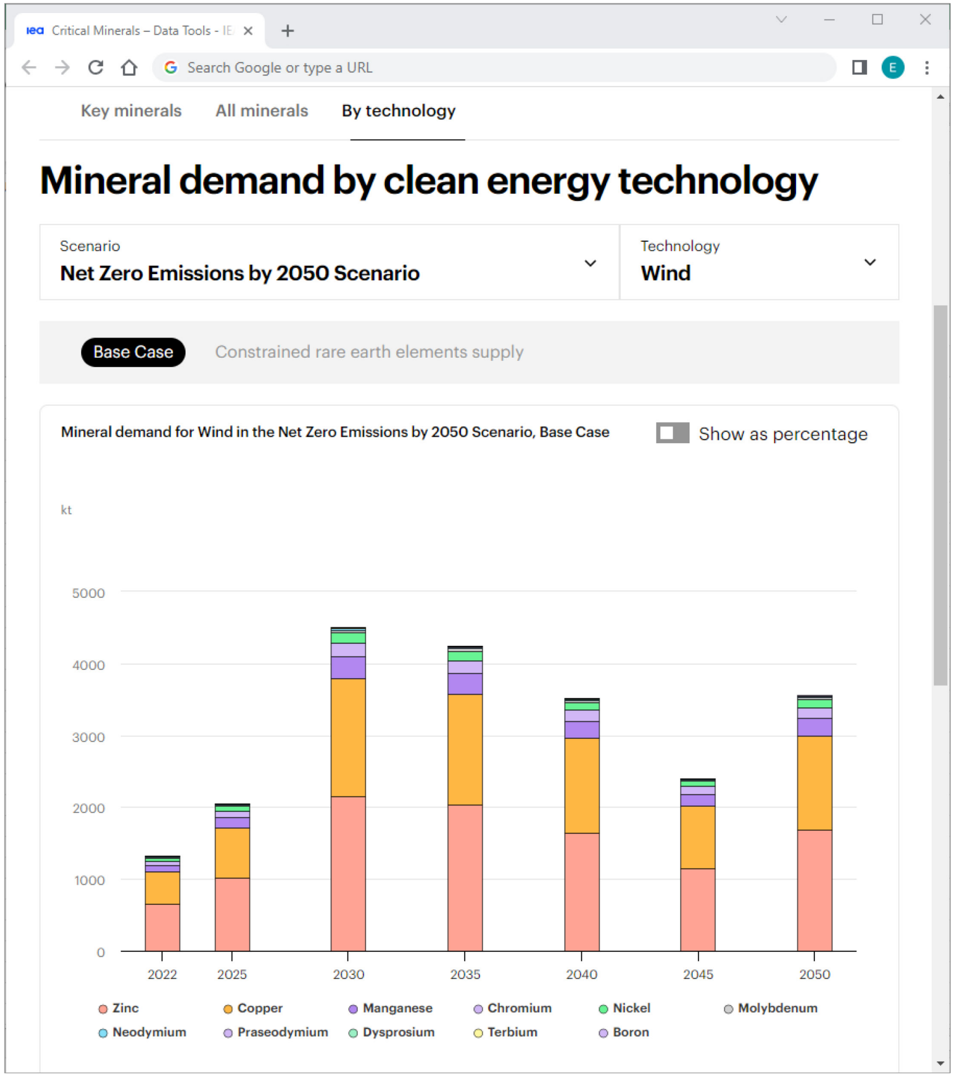
Annex

IEA Critical Minerals Data Explorer

The International Energy Agency (IEA) has integrated critical minerals into its long-term energy modelling framework. In 2023, the IEA Critical Minerals Data Explorer, an interactive online tool that allows users to easily access the IEA's projections, was launched and has been regularly updated since then. In 2024, the Data Explorer was updated to also include long-term supply projection data as well as demand projection data for the key energy minerals such as 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 and sectoral demand for key energy minerals by scenario and technology case. Long-term supply projections for the key energy minerals are also accessible in the tool.

The numbers are regularly updated to align with the latest energy projections, and will be updated again when the World Energy Outlook 2025 is released.

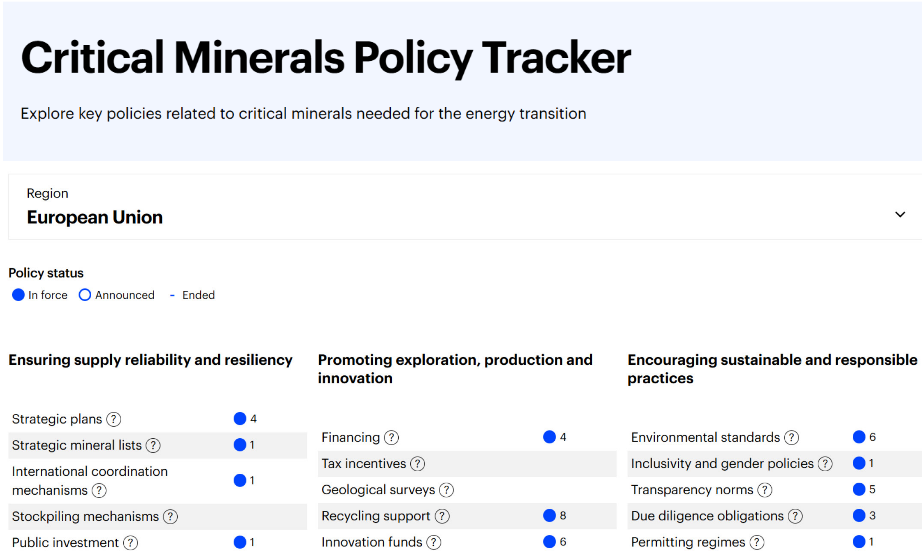


IEA Critical Minerals Policy Tracker

The IEA launched the Critical Minerals Policy Tracker in November 2022 to monitor and analyse policy developments on critical minerals. This tool, which is updated regularly, tracks policies across more than 35 countries, starting from an initial dataset of 200 policies and expanded to over 500 policies.

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. 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.



In 2024, policies were added coinciding with the release of the Global Critical Minerals Outlook 2024 and Recycling of Critical Minerals. Recycling policies were categorised into four categories, namely strategic plans, extended producer responsibility, financial incentives and cross-border trade. In 2025, policies were also added with the release of The Role of Traceability in Critical Mineral Supply Chains as well as the Global Critical Minerals Outlook 2025.

The Critical Minerals Policy Tracker provides an overview of the evolving landscape in mineral supply chain policies and governance in the context of energy transitions.

Methodology

Scope

The critical minerals model, linked closely with the Global Energy and Climate (GEC) Model, assesses the mineral requirements for the following clean energy technologies:

- low-emissions power generation
    - solar photovoltaic (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, motors)
- 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 focus minerals – copper, lithium, nickel, cobalt, graphite and rare earth elements – we model total demand including uses in energy applications and other segments. Consumption outside the energy sector has been estimated using historical consumption by end-use applications, relevant activity drivers (e.g. gross domestic product [GDP], industry value added, steel production) and material intensities.

Demand

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

- technology 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 2024, adjusted by latest information from the Global EV Outlook 2025 and other sources.

Mineral intensity assumptions are developed and continuously refined through extensive literature reviews 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 to modest improvement (around 10% in the longer term) assumed in the APS and the 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

Supply projections for the six key energy minerals is built using the data for the pipeline of operating and announced mining and refining projects by country. These projections are divided into a base 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.

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.

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.

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

Key projection results

Copper demand

	Historical		Stated Policies			Announced Pledges			Net Zero Emissions by 2050		
Unit: kt Cu	**2021**	**2024**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Clean energy	6 002	7 737	10 910	12 162	13 042	12 578	16 352	17 176	15 166	19 846	19 679
Electricity networks	4 652	4 929	5 825	5 745	5 641	6 543	8 073	7 479	7 723	9 972	8 853
Electric vehicles	165	497	1 597	2 995	3 505	1 789	3 976	4 743	2 665	5 219	5 676
Solar PV	702	1 657	2 374	2 230	2 377	2 803	2 626	2 758	2 849	2 570	2 734
Other	482	654	1 115	1 192	1 518	1 443	1 676	2 196	1 929	2 085	2 416
Other uses	18 944	18 980	20 438	21 975	24 409	20 042	20 388	22 465	19 250	19 634	21 598
Total demand	24 946	26 717	31 348	34 137	37 451	32 620	36 740	39 641	34 416	39 480	41 277
Share of clean energy	24%	29%	35%	36%	35%	39%	45%	43%	44%	50%	48%

Notes: kt = kilotonnes. Demand is based on refined copper and excludes direct use of scrap. Electric vehicles demand includes both EV battery and EV motor demand.

Copper supply

	Mining					Refining			
	Historical		Base case			Historical		Base case	
Unit: kt Cu	2021	2024	2030	2040		2021	2024	2030	2040
Chile	5 663	5 476	5 505	4 164	China	10 383	11 860	15 688	15 688
DRC	2 017	2 876	3 578	2 156	DRC	2 017	2 876	3 578	2 156
Peru	2 284	2 631	2 425	1 138	Chile	2 273	1 966	1 867	1 294
China	1 832	1 815	1 962	1 676	Japan	1 514	1 578	1 614	1 614
Russia	867	1 101	1 194	998	India	498	655	1 060	1 060
Indonesia	753	1 069	997	834	-				
Rest of world	8 029	7 826	7 396	4 078	Rest of world	8 289	8 009	9 859	9 331
World	21 445	22 794	23 057	15 044	World	24 974	26 944	33 666	31 143
Top 3 share	46%	48%	50%	53%	Top 3 share	57%	59%	60%	60%

Note: DRC = Democratic Republic of the Congo.

Lithium demand

Unit: kt Li	Historical		Stated Policies			Announced Pledges			Net Zero Emissions by 2050		
	2021	2024	2030	2040	2050	2030	2040	2050	2030	2040	2050
Clean energy	38	128	369	809	1 019	418	1 081	1 389	615	1 427	1 683
Electric vehicles	35	109	326	739	930	369	993	1 276	556	1 318	1 547
Battery storage	2	19	43	70	89	48	88	113	58	109	137
Other uses	57	77	87	119	150	87	119	150	87	119	150
Total demand	95	205	455	928	1 170	505	1 200	1 540	701	1 546	1 834
Share of clean energy	40%	62%	81%	87%	87%	83%	90%	90%	88%	92%	92%

Lithium supply

	Raw materials					Chemicals			
	Historical		Base case			Historical		Base case	
Unit: kt Li	2021	2024	2030	2040		2021	2024	2030	2040
Australia	50	90	124	101	**China**	70	170	277	282
China	17	57	134	125	**Chile**	25	49	58	60
Chile	28	49	58	60	**Argentina**	7	13	49	51
Argentina	6	13	49	51	**Australia**	0	4	24	26
Zimbabwe	2	23	33	26	**United States**	1	3	27	27
Canada	0	6	25	23	**Germany**	0	2	6	7
Rest of world	4	17	49	32	**Rest of world**	0	1	9	9
World	107	255	471	418	**World**	103	242	450	461
Top 3 share	89%	77%	67%	69%	**Top 3 share**	99%	96%	85%	85%

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.

Nickel demand

	Historical		Stated Policies			Announced Pledges			Net Zero Emissions by 2050		
Unit: kt Ni	**2021**	**2024**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Clean energy	226	562	1 349	2 381	2 790	1 647	3 201	4 033	2 415	4 103	4 497
Electric vehicles	150	321	959	1 844	2 146	1 083	2 475	2 942	1 561	3 153	3 427
Battery storage	7	17	68	189	377	77	238	480	93	293	578
Other	69	224	322	349	268	486	488	611	762	657	491
Other uses	2 600	2 809	3 039	3 304	3 547	2 974	3 033	3 197	2 947	2 976	3 115
Total demand	2 825	3 371	4 389	5 685	6 337	4 620	6 233	7 230	5 363	7 079	7 612
Share of clean energy	8%	17%	31%	42%	44%	36%	51%	56%	45%	58%	59%

Nickel supply

Unit: kt Ni	Mining					Refining			
	Historical		Base case			Historical		Base case	
	2021	2024	2030	2040		2021	2024	2030	2040
Indonesia	1 105	2 463	3 042	3 343	**Indonesia**	907	1 493	2 037	2 045
Philippines	476	345	268	268	**China**	746	1 091	1 480	1 480
Russia	205	190	220	220	**Japan**	128	114	107	107
New Caledonia	186	116	212	212	**Russia**	121	126	142	142
Canada	134	118	147	52	**Finland**	49	62	86	86
China	108	134	148	135	**Canada**	113	113	128	84
Australia	151	100	40	40	**Australia**	99	80	37	37
Rest of world	423	424	433	287	**Rest of world**	544	404	485	445
World	2 788	3 890	4 510	4 557	**World**	2 709	3 484	4 503	4 428
Top 3 share	64%	77%	78%	84%	**Top 3 share**	66%	78%	81%	83%

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 Emissions by 2050		
Unit: kt Co	**2021**	**2024**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Clean energy	37	71	148	136	172	168	184	240	243	248	292
Electric vehicles	35	67	143	136	172	162	184	240	236	248	292
Battery storage	2	4	5	0	0	6	0	0	7	0	0
Other uses	150	154	166	194	218	165	190	213	164	190	212
Total demand	187	221	314	330	390	332	374	453	408	437	503
Share of clean energy	20%	32%	47%	41%	44%	50%	49%	53%	60%	57%	58%

Cobalt supply

	Mining					Refining			
	Historical		Base case			Historical		Base case	
Unit: kt Co	2021	2024	2030	2040		2021	2024	2030	2040
DRC	121	182	199	108	China	128	196	252	254
Indonesia	3	33	58	59	Finland	14	20	20	20
Russia	6	6	8	8	Japan	5	6	6	6
China	7	7	8	7	Indonesia	0	3	10	11
Australia	8	6	6	5	Canada	7	2	4	7
Philippines	5	6	3	3	Korea	4	4	6	7
Rest of world	30	33	37	24	Rest of world	24	19	27	29
World	179	273	321	214	World	182	250	325	333
Top 3 share	76%	81%	83%	82%	Top 3 share	86%	89%	87%	86%

Note: DRC = Democratic Republic of the Congo.

Graphite demand

	Historical		Stated Policies			Announced Pledges			Net Zero Emissions by 2050		
Unit: kt	**2021**	**2024**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Clean energy	487	1 505	4 114	5 700	3 548	4 664	7 608	4 816	6 898	10 343	6 164
Electric vehicles	454	1 260	3 598	4 784	2 587	4 079	6 451	3 590	6 190	8 918	4 688
Battery storage	33	246	516	917	961	585	1 157	1 225	707	1 425	1 476
Other uses	3 326	3 260	4 105	5 309	6 370	4 149	5 490	6 730	4 242	5 714	6 914
Total demand	3 813	4 766	8 219	11 010	9 918	8 813	13 098	11 546	11 140	16 057	13 078
Share of clean energy	13%	32%	50%	52%	36%	53%	58%	42%	62%	64%	47%

Note: Demand covers raw natural flake graphite and synthetic graphite.

Graphite supply

	Mining (natural graphite)					Refined battery-grade supply			
	Historical		Base case			Historical		Base case	
Unit: kt	2021	2024	2030	2040		2021	2024	2030	2040
China	1 140	1 580	1 261	1 436	China	638	1 795	3 854	3 811
Mozambique	77	38	210	289	Japan	41	45	159	187
Madagascar	82	73	239	223	United States	0	1	32	52
Russia	28	30	33	50	Canada	0	0	9	29
Tanzania	0	9	32	39	Sweden	0	0	1	4
Canada	9	12	0	0	Finland	0	0	1	8
Rest of world	114	106	217	227	Rest of world	4	34	371	399
World	1 451	1 847	1 991	2 264	World	683	1 875	4 427	4 490
Top 3 share	90%	93%	86%	86%	Top 3 share	100%	99%	93%	92%

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 Emissions by 2050		
Unit: kt REE	**2021**	**2024**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Clean energy	11	19	38	47	57	47	60	77	63	71	80
Electric vehicles	3	8	22	34	39	23	42	50	32	49	54
Wind	8	10	16	13	17	24	18	27	31	21	26
Other uses	67	72	85	103	121	85	103	121	84	102	120
Total demand	78	91	123	150	178	132	163	197	147	172	200
Share of clean energy	14%	20%	31%	31%	32%	36%	37%	39%	43%	41%	40%

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	2024	2030	2040		2021	2024	2030	2040
China	30	42	51	57	China	53	74	81	86
Myanmar	8	12	11	11	Malaysia	4	4	10	10
United States	6	7	9	9	United States	0	1	7	9
Australia	4	3	13	15	Australia	0	0	3	3
Lao PDR	0	3	8	8	Viet Nam	1	1	1	1
Rest of world	6	4	9	9	Rest of world	1	1	5	5
World	54	71	100	109	World	59	81	107	115
Top 3 share	80%	86%	74%	76%	Top 3 share	98%	97%	92%	92%

Notes: Lao PDR = Lao People's Democratic Republic. Rare earth elements refer only to four magnet rare earths, neodymium, praseodymium, dysprosium and terbium.

Acknowledgements

This report was prepared by the Office of the Chief Energy Economist of the Directorate of Sustainability, Technology and Outlooks, in co-operation with other directorates of the International Energy Agency (IEA). Tae-Yoon Kim co-ordinated the work and was the lead author, and he designed and directed the report together with Tim Gould, Chief Energy Economist.

The principal authors from across the agency were: Eric Buisson (lithium, graphite, broader strategic minerals, demand modelling), Amrita Dasgupta (rare earth elements, supply-side technology innovation, renewables), Shobhan Dhir (battery supply chains and EVs, copper, manganese, security implications), Félix Gagnon (policy tracking, regional snapshot, environmental and social issues), Alexandra Hegarty (nickel, cobalt, policy mechanisms for diversifcation, sustainability performance tracking), Gyubin Hwang (policy mechanisms for diversifcation, supply-side technology innovation, uranium), K.C. Michaels (policy and regulatory developments), Kentaro Miwa (battery supply chains, supply-side technology innovation, trading, aluminium), Nicolas Moinier (regional snapshot, sustainable performance tracking), Mari Nishiumi (broader strategic minerals, regional analysis for China and Japan, platinum-group metals), Tomás de Oliveira Bredariol (sustainability performance tracking), Ryszard Pospiech (data), Joyce Raboca (policy tracking, regional snapshot, environmental and social issues), Sungmin Seo (silver, investment, cost analysis) and Wonjik Yang (infographic). Davina Till and Eleni Tsoukala provided essential support.

The report benefited greatly from contributions from other experts within the IEA: Mary Warlick, Laura Cozzi, Keisuke Sadamori, Timur Gül, Pascal Laffont, Alessandro Blasi, Jason Elliott, Dennis Hesseling, Simon Bennett, Eléonore Carre, Alexandre Gouy, Sadhika Gulati, Milosz Karpinski, Alara Kocabas, Teo Lombardo and Alessio Scanziani.

Thanks also to Jethro Mullen, Curtis Brainard, Astrid Dumond, Merve Erdil, Julia Horowitz, Liv Gaunt, Grace Gordon, Clara Vallois and Lucile Wall of the Communications and Digital Office. Erin Crum edited the manuscript and Poeli Bojorquez designed the cover. Jon Custer and Ivo Letra provided support for the web-based data tool.

This analysis has been supported by the Clean Energy Transitions Programme, the IEA's flagship initiative to transform the world's energy system to achieve a secure and sustainable future for all. The work also benefited from the financial support provided by the Ministry of Foreign Affairs of Korea. Thanks also go to the IEA Working Party on Critical Minerals and the IEA Critical Minerals Expert Advisory Group who provided valuable input to the design of the report. Data on manganese sulphate and phosphoric acid were provide by courtesy of Benchmark Mineral Intelligence. Data on emissions intensity and copper risk exposure data were provided by courtesy of Skarn Associates.

Many experts from outside of the IEA provided essential input and/or reviewed preliminary drafts of the report. Their comments and suggestions were of great value. They include:

Siyamend Al Barazi	BGR Germany
David Anonychuk	Société Générale de Surveillance (SGS)
Tsutomu Aoki	Toyota
Jeffrey Biggs	Natural Resources Canada
Stephane Bourg	BRGM
Vincenzo Conforti	Glencore
Clint Cox	The Anchor House
Raphaël Danino-Perraud	Institut Français des Relations Internationales (IFRI)
Stefan Debruyne	SQM
Sylvain Eckert	Infravia
Colin Hamilton	Teck Resources
Peter Handley	PHASE 32
Takeshi Harada	Japan Organisation for Metals and Energy Security (JOGMEC)
Masaya Hanzawa	Battery Association for Supply Chain
Corina Hebestreit	European Carbon and Graphite Association
Jihyun Kim	Samsung SDI
Hyunbock Lee	Korea Institute of Geoscience and Mineral Resources
John Lindberg	International Council on Mining and Metals (ICMM)
Sophie Lu	HSBC
Dennis O. Mesina	U.S. Department of Energy
Tom Moerenhout	Columbia University, Center on Global Energy Policy
Jane Nakano	Center for Strategic and International Studies
Yasuko Nishimura	Ministry of Foreign Affairs of Japan
Julia Poliscanova	Transport and Environment

Mark Richards	Rio Tinto
Matt Sloustcher	MP Materials
Matthew Teh	Department of Industry, Science and Resources of Australia
Lyle Trytten	Trytten Consulting
Constanze Veeh	European Commission
Ke Wang	World Resources Institute
Yuzo Yamaguchi	Ministry of Economy, Trade and Industry of Japan

The work reflects the views of the IEA Secretariat, but does not necessarily reflect those of reviewers. Any funder, supporter or collaborator that contributed to this work shall not be responsible for any use of, or reliance on, the work.

Abbreviations and acronyms

AI	artificial Intelligence
APS	Announced Pledges Scenario
AUD	Australian dollar
ASSB	all solid-state battery
BEV	battery electric vehicle
BRI	Belt and Road Initiative
BRL	Brazilian Real
CAD	Canadian dollar
CAGR	compound annual growth rate
CAM	cathode active material
CATL	Contemporary Amperex Technology Co., Limited
CfDs	contract for differences
CME	Chicago Mercantile Exchange
CMOC	CMOC Group Limited
CNY	Chinese Yuan/renminbi
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
CRMA	Critical Raw Materials Act
CSAM	Central and South America
CTP	cell-to-pack
DFC	International Development Finance Corporation
DLE	direct lithium extraction
DoD	Department of Defense
DRC	Democratic Republic of the Congo
Dy	Dysprosium
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
EXIM	Export-Import Bank
GHG	greenhouse gas
HALEU	high-assay low-enriched uranium
HMS	heavy mineral sand
HPAL	high pressure acid leaching
HREE	heavy rare earth element
HSI	hyperspectral imaging
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
ISA	International Seabed Authority
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
JOGMEC	Japan Organisation for Metals and Energy Security
JV	joint venture
Korea	Republic of Korea

Lao PDR	Lao People's Democratic Republic
LCE	lithium carbonate equivalent
LDV	light-duty vehicle
LFP	lithium iron phosphate
LME	London Metal Exchange
LMFP	lithium manganese iron phosphate
LMR-NMC	lithium-manganese-rich NMC
LNMO	lithium nickel manganese oxide
LNO	lithium nickel oxide
LREE	light rare earth elements
M&A	mergers and acquisitions
MoU	memorandum of understanding
MSP	mixed sulphide precipitate
Na-ion	sodium-ion
NCA	nickel cobalt aluminium
NCMM	National Critical Mineral Mission
Nd	neodymium
NDC	nationally determined contribution
NdFeB	neodymium iron boron
NMC	nickel manganese cobalt
NMCA	nickel manganese cobalt aluminium oxide
NORI	Nauru Ocean Resources Inc.
NZE	Net Zero Emissions By 2050 Scenario
OECD	Organisation For Economic Co-operation and Development
OEM	original equipment manufacturer
PAL	pressure acid leaching
PBAs	Prussian blue analogues
pCAM	precursor cathode active material
PEM	proton exchange membrane
PGMs	platinum-group metals
PHEV	plug-in hybrid electric vehicles
Pr	praseodymium
PV	photovoltaic
R&D	research and development
REE	rare earth element
REO	rare earth oxides
RIGI	Large Investment Incentive Regime
SASB	Sustainability Accounting Standards Board
SDG	sustainable development goal
SHFE	Shanghai Futures Exchange
Si-Gr	silicon and graphite
SmCo	samarium-cobalt
SPV	special purpose vehicle
STEPS	Stated Policies Scenario
SxEw	solvent extraction and electrowinning
Tb	terbium
TMC	The Metals Company
TRL	technology readiness level
U-235	uranium-235
UK	United Kingdom
UNCLOS	United Nations Convention on the Law of the Sea
US	United States
USD	United States dollar
USMCA	US-Mexico-Canada Agreement
VC	venture capital
ZIMIS	Zambia Integrated Mining Information System

Units of measure

g	grammes
g/cm^3	grammes per cubic centimetre
GJ/t	gigajoules per tonne
Gt	gigatonne
GW	gigawatt
GWh	gigawatt-hour
kg	kilogramme
km	kilometre
kt	kilotonne
ktpa	kilotonnes per annum
kWh	kilowatt-hour
m	metre
m^3	cubic metre
mcm	million cubic metres
Mt	million tonnes
tCO_2-eq	tonnes of CO_2-equivalent
tCO_2	tonnes of carbon dioxide
toz	troy ounce
Mtpa	million tonnes per annum
MW	megawatt
TWh	terawatt-hours

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Typeset in France by IEA - May 2025
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Revised version, June 2025
Information notice found at: www.iea.org/corrections