

Critical Minerals Market Review 2023



INTERNATIONAL ENERGY AGENCY

The IEA examines the full spectrum of energy issues including oil, gas and coal supply and demand, renewable energy technologies, electricity markets, energy efficiency, access to energy, demand side management and much more. Through its work, the IEA advocates policies that will enhance the reliability, affordability and sustainability of energy in its 31 member countries, 11 association countries and beyond.

This publication and any map included herein are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

IEA member countries:

Australia
Austria
Belgium
Canada
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Ireland
Italy
Japan
Korea
Lithuania
Luxembourg
Mexico
Netherlands
New Zealand
Norway
Poland
Portugal
Slovak Republic

Spain
Sweden
Switzerland
Republic of Türkiye
United Kingdom
United States

The European Commission
also participates in the work
of the IEA

IEA association countries:

Argentina
Brazil
China
Egypt
India
Indonesia
Kenya
Morocco
Senegal
Singapore
South Africa
Thailand
Ukraine

Source: IEA.
International Energy Agency
Website: www.iea.org

Abstract

The inaugural edition of the *Critical Minerals Market Review* provides a major update on the investment, market, technology and policy trends of the critical minerals sector in 2022 and an initial reading of the emerging picture for 2023. Through in-depth analyses of clean energy and mineral market trends, this report assesses the progress made by countries and businesses in scaling up future supplies, diversifying sources of supply, and improving sustainable and responsible practices. It also examines major trends for individual minerals and discusses key policy implications.

The report will be followed by a forthcoming analysis that will feature comprehensive demand and supply projections for key materials and a number of deep-dives on key issues. It also makes available an online tool, the [Critical Minerals Data Explorer](#), which allow users to explore interactively the latest IEA projections.

Table of content

Introduction 4

Executive summary 5

Key market developments 9

Developments of the battery sector 35

Key trends by individual commodity 50

Implications 62

Annex 75

Introduction

Critical minerals, essential for a range of clean energy technologies, have risen up the policy and business agenda in recent years. Rapid growth in demand is providing new opportunities for the industry, but a combination of volatile price movements, supply chain bottlenecks and geopolitical concerns has created a potent mix of risks for secure and rapid energy transitions. This has triggered an array of new policy actions in different jurisdictions to enhance the diversity and reliability of critical mineral supplies.

Since the International Energy Agency's (IEA) landmark analysis on the [Role of Critical Minerals in Clean Energy Transitions](#) and the new [ministerial mandates](#) in March 2022, the Agency has expanded its work on critical minerals to help policymakers address these emerging challenges and ensure reliable and sustainable supplies of critical minerals. These efforts include a commitment to regular market monitoring, which aims to provide a clear understanding of today's demand and supply dynamics and what they mean for the future. In this inaugural piece of analysis, we review the latest price, investment and production trends in the critical minerals sector. The first chapter provides a snapshot of industry developments in 2022 and early 2023. The second chapter reviews key trends in the battery sector given its importance in driving demand growth for critical minerals. The third chapter presents a concise review of key trends for each individual commodity. In the final chapter, we present implications for policy and industry stakeholders.

Critical minerals have been fully integrated into the IEA's [Global Energy and Climate Model](#), which means that the projections for critical minerals demand and supply are regularly updated in line with latest policy and technology trends in the IEA energy scenarios, notably in the [World Energy Outlook](#) and the [Global EV Outlook](#). The updated projections are available through the [IEA Critical Minerals Data Explorer](#), an online tool that intends to allow users to easily access and navigate the latest data. This is part of the efforts to enhance market transparency through making more data publicly available.

Our report considers a wide range of minerals used in clean energy technologies, as indicated in the Annex of the [special report](#). For energy transition minerals, we focus on copper, major battery metals (lithium, nickel, cobalt and graphite) and rare earth elements. We also discuss trends for other important minerals and metals such as aluminium, manganese, platinum group metals and uranium as relevant.

This report focuses on today's state of play. It will be complemented by a forthcoming piece of analysis that will provide full demand and supply projections for key materials and a number of deep-dives on key issues. This will respond directly to the request in the [G7 Five-Point Plan](#) for critical minerals security, where the Group of Seven ministers asked the IEA to produce medium- and long-term outlooks for critical minerals demand and supply to help inform decision making.

Executive summary

Record deployment of clean energy technologies such as solar PV and batteries is propelling unprecedented growth in the critical minerals markets. Electric car sales increased by 60% in 2022, exceeding 10 million units. Energy storage systems experienced even more rapid growth, with capacity additions doubling in 2022. Solar PV installations continue to shatter previous records, and wind power is set to resume its upward march after two subdued years. This has led to a significant increase in demand for critical minerals. From 2017 to 2022, demand from the energy sector was the main factor behind a tripling in overall demand for lithium, a 70% jump in demand for cobalt, and a 40% rise in demand for nickel. In 2022, the share of clean energy applications in total demand reached 56% for lithium, 40% for cobalt and 16% for nickel, up from 30% for lithium, 17% for cobalt and 6% for nickel five years ago.

Driven by rising demand and high prices, the market size of key energy transition minerals doubled over the past five years, reaching USD 320 billion in 2022. This contrasts with the modest growth of bulk materials like zinc and lead. As a result, energy transition minerals, which used to be a small segment of the market, are now moving to centre stage in the mining and metals industry. This brings new revenue opportunities for the industry, creates jobs for the society, and in some cases helps diversify coal-dependent economies.

The affordability and speed of energy transitions will be heavily influenced by the availability of critical mineral supplies. Many

critical minerals experienced broad-based price increases in 2021 and early 2022, accompanied by strong volatility, particularly for lithium and nickel. Most prices began to moderate in the latter half of 2022 and into 2023 but remain well above historical averages. Higher or volatile mineral prices during 2021 and 2022 highlighted the importance of material prices in the costs of transforming our energy systems. According to the IEA's clean energy equipment price index, clean energy technology costs continued to decline until the end of 2020 due to technology innovation and economies of scale, but high material prices then reversed this decade-long trend. Despite these recent setbacks, it is noteworthy that the prices of all clean energy technologies today are significantly lower than a decade ago.

Countries are seeking to diversify mineral supplies with a wave of new policies. There is growing recognition that policy interventions are needed to ensure adequate and sustainable mineral supplies and the proliferation of such initiatives includes the European Union's [Critical Raw Materials \(CRM\) Act](#), the United States' [Inflation Reduction Act](#), Australia's [Critical Minerals Strategy](#) and Canada's [Critical Minerals Strategy](#), among others. The [IEA Critical Minerals Policy Tracker](#) identified nearly 200 policies and regulations across the globe, with over 100 of these enacted in the past few years. Many of these interventions have implications for trade and investment, and some have included restrictions on import or export. Among resource-rich countries, [Indonesia](#), [Namibia](#) and [Zimbabwe](#) have introduced measures to ban

the export of unprocessed mineral ore. Globally, export restrictions on critical raw materials have seen a [fivefold increase](#) since 2009.

Investment in critical minerals development recorded another sharp uptick by 30% in 2022, following a 20% increase in 2021. Our detailed analysis of the investment levels of 20 large mining companies with a significant presence in developing energy transition minerals shows a strong rise in capital expenditure on critical minerals, spurred by the robust momentum behind clean energy deployment. Companies specialising in lithium development recorded a 50% increase in spending, followed by those focusing on copper and nickel. Companies based in the People's Republic of China (hereafter, "China") nearly doubled their investment spending in 2022.

Exploration spending also rose by 20% in 2022, driven by record growth in lithium exploration. Canada and Australia led the way with over 40% growth year-on-year, notably in hard-rock lithium plays. Exploration activities are also expanding in Africa and Brazil. Lithium stood out as a clear leader in exploration activities, with spending increasing by 90%. Uranium also experienced a significant surge in spending by 60% due to renewed interest in nuclear power amid concerns over Russian supplies. Nickel was a close follower with a 45% growth rate for exploration, led by Canada, where high-grade sulfide resources, proximity to existing infrastructure and access to low-emissions electricity create attractive investment opportunities.

Despite headwinds in the wider venture capital sector, critical minerals start-ups raised a record USD 1.6 billion in 2022. This 160% year-on-year increase took the critical minerals category to 4% of

all venture capital (VC) funding for clean energy. The first quarter of 2023 has been strong for critical minerals, despite a severe downturn in other VC segments, such as digital start-ups. Battery recycling was the largest recipient of VC funding, followed by lithium extraction and refining technologies. Companies based in the United States raised most of the funds, at 45% of the total between 2018 and 2022. Canadian and Chinese start-ups are notably active in battery recycling and lithium refining. European start-ups have been successful at raising money for rare earth elements, battery reuse and battery material supply.

The battery sector is undergoing transformative changes with the emergence of new technology options. Global battery demand for clean energy applications increased by two-thirds in 2022, with energy storage becoming a growing part of the total demand. Demand for batteries in vehicles outpaced the growth rate of electric car sales as the average battery size for electric cars continued to rise in nearly every major market. The trend of favouring larger vehicles seen in conventional car markets is [being replicated in the EV market](#), posing additional pressure on critical mineral supply chains. Sodium-ion batteries witnessed a leap forward in early 2023, with plans for production capacity exceeding [100 gigawatt-hours](#), primarily concentrated in China. Initially, companies are targeting less demanding applications such as stationary storage or micromobility for this technology, and it remains to be seen if it will be able to meet the needs for EV range and charging time. Today, the vast majority of recycling capacity is located in China, but new facilities are being developed in Europe and the United States. Scrap from manufacturing processes is

dominating today's recycling pool, but this is set to change from around 2030 as used EV batteries reach the end of their first life.

In a bid to secure mineral supplies, automakers, battery cell makers and equipment manufacturers are increasingly getting involved in the critical minerals value chain. Long-term offtake agreements have become the norm in the industry's procurement strategies, but companies are taking extra steps to invest directly in the critical minerals value chain such as mining, refining and precursor materials. Since 2021, there has been a notable increase in direct investment activities. Contemporary Amperex Technology Co. Limited, the world's largest battery cell maker, has made the acquisition of critical mineral assets a central element of its strategy. Other examples include General Motors' USD 650 million investment in [Lithium Americas](#) and Tesla's plan to build a [new lithium refinery](#) in the United States, among others.

Demand for critical minerals for clean energy technologies is set to increase rapidly in all IEA scenarios. Since its landmark [special report](#) in 2021, the IEA has been updating its projections for future mineral demand based on the latest policy and technology developments. In the Announced Pledges Scenario (APS), demand more than doubles by 2030. In the Net Zero Emissions by 2050 (NZE) Scenario, demand for critical minerals grows by three and a half times to 2030, reaching over 30 million tonnes. EVs and battery storage are the main drivers of demand growth, but there are also major contributions from low-emissions power generation and electricity networks. These results are available through the [IEA Critical Minerals Data Explorer](#), an interactive online tool that allows users to easily access the IEA's projection data under different scenarios and technology trends.

Three layers of supply-side challenges need to be addressed to ensure rapid and secure energy transitions. They are i) whether future supplies can keep up with the rapid pace of demand growth in climate-driven scenarios; ii) whether those supplies can come from diversified sources; and iii) whether those volumes can be supplied from clean and responsible sources.

A host of newly announced projects indicate that supply is catching up with countries' clean energy ambitions, but the adequacy of future supply is far from assured. In some cases, newly announced projects suggest that anticipated supplies in 2030 are approaching the requirements of the APS although deployment levels in the NZE Scenario require further projects to be realised. While encouraging, practical challenges persist. Risks of schedule delays and cost overruns, which have been prevalent in the past, cannot be ignored. There is also an important distinction between technology-grade products and battery-grade products, with the latter generally requiring higher-quality inputs. This means that even with an overall balance of supply and demand, the supply of battery-grade products may still be constrained. Moreover, new mining plays often come with higher production costs, which could push up marginal costs and prices.

Limited progress has been made in terms of diversifying supply sources in recent years; the situation has even worsened in some cases. Compared with the situation three years ago, the share of the top three producers in 2022 either remains unchanged or has increased further, especially for nickel and cobalt. Our analysis of project pipelines indicates a somewhat improved picture for mining, but not for refining operations where today's geographical concentration is greater. The

majority of planned projects are developed in incumbent regions, with China holding half of planned lithium chemical plants and Indonesia representing nearly 90% of planned nickel refining facilities. Many resource-holding nations are seeking positions further up the value chain while many consuming countries want to diversify their source of refined metal supplies. However, the world has not yet successfully connected the dots to build diversified midstream supply chains.

There has been mixed progress towards improving sustainable and responsible practices. Some companies are stepping up actions to reduce environmental and social harms associated with their activities. Our assessment of the environmental and social performance of 20 key companies shows that companies are making headway in community investment, worker safety and gender balance. However, environmental indicators are not improving at the same rate. Greenhouse gas emissions remain high, with roughly the same amount being emitted per tonne of mineral output every year. Water withdrawals almost doubled from 2018 to 2021. There is also a question mark regarding the extent to which sustainability is being seriously considered by consumers. Despite the availability of cleaner production pathways, there are few signs that end users are prioritising them in their sourcing and investment decisions, although some downstream companies have started to give preference to minerals with a lower climate impact.

Critical minerals supply is also a concern for China. As the world's largest metal refining hub, China heavily relies on imports for large volumes of raw materials, often from a small number of sources. For example, China relies almost entirely on the Democratic Republic of the Congo for mined cobalt. China is therefore seeking ways to diversify its

raw material supply portfolio. The country has been actively investing in mining assets in Africa and Latin America, and started investing in overseas refining and downstream facilities, with an aim to secure strategic access to raw materials. Between 2018 and the first half of 2021, Chinese companies invested [USD 4.3 billion](#) to acquire lithium assets, twice the amount invested by companies from the United States, Australia and Canada combined during the same period.

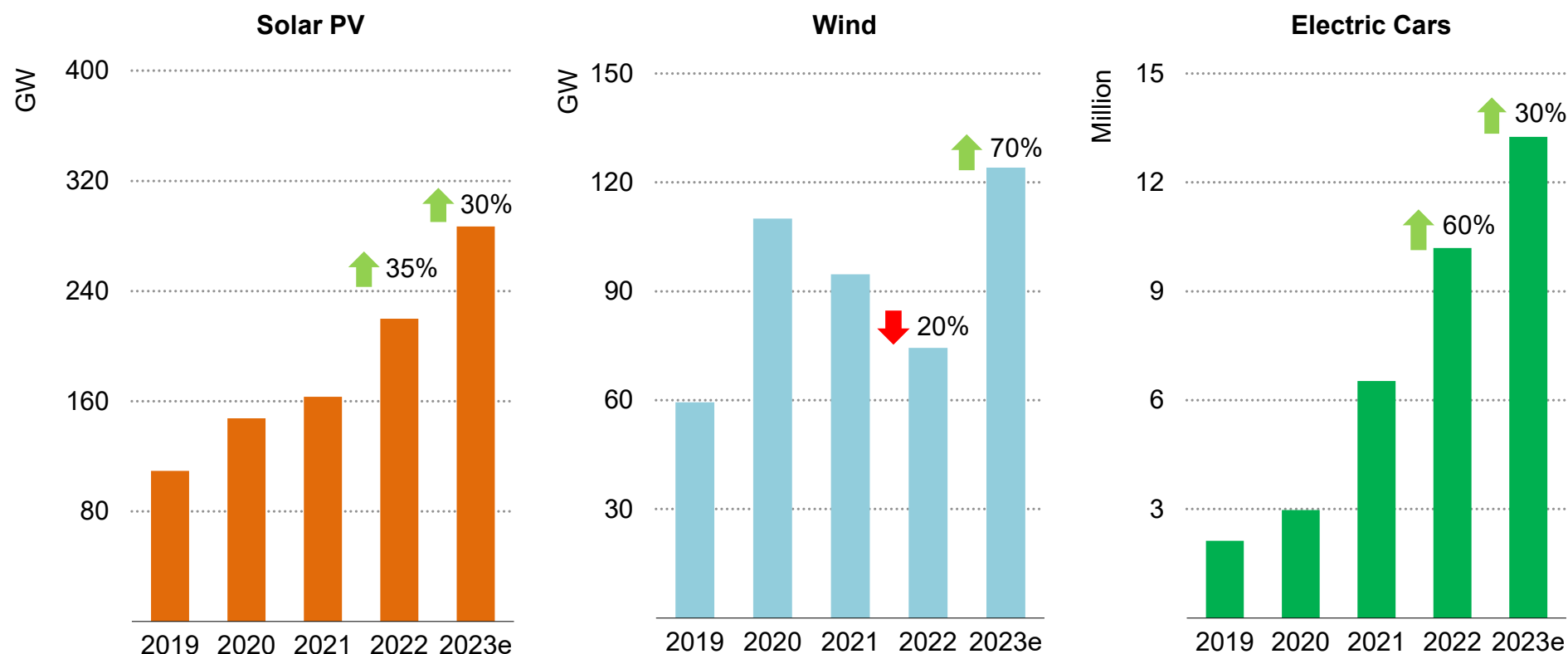
An approach to critical mineral security needs to cast its net widely to encompass niche minerals. While the focus has understandably been on battery metals and copper, recent events such as [the export curbs on Chinese gallium and germanium in July 2023](#) have highlighted the significance of a lesser-known group of critical minerals, often characterised by small volumes, but high levels of supply concentration. These illustrate how relatively niche minerals such as magnesium, high-purity manganese, high-purity phosphorus and silicon may disrupt supply chains due to high reliance on a small group of suppliers.

A broad and bold strategy is needed that brings together investment, innovation, recycling, rigorous sustainability standards and well-designed safety nets. To bolster global progress, the IEA will host [the first-ever international summit on critical minerals](#) on 28 September 2023, bringing together ministers from mineral-producing and -consuming economies as well as industry, investors and civil society to discuss measures for collectively promoting a secure and sustainable supply of critical minerals.

Key market developments

Clean energy technology deployment continued its upward march in 2022, with momentum expected to continue through 2023 and beyond

Annual capacity additions for solar PV and wind and electric car sales

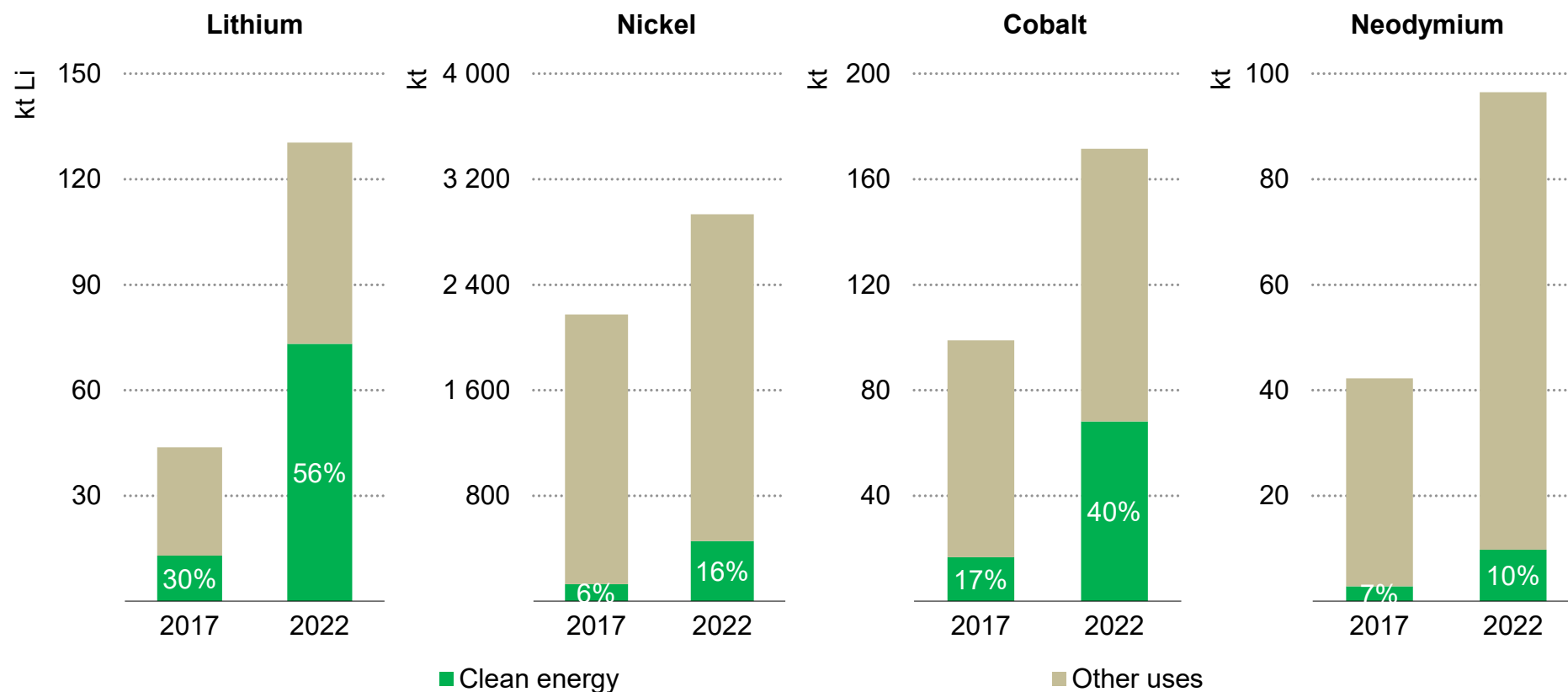


IEA. CC BY 4.0.

Source: IEA (2023), [Renewable Energy Market Update – June 2023](#), for solar PV and wind capacity additions; IEA (2023), [Global EV Outlook 2023 – April 2023](#), for electric car sales.

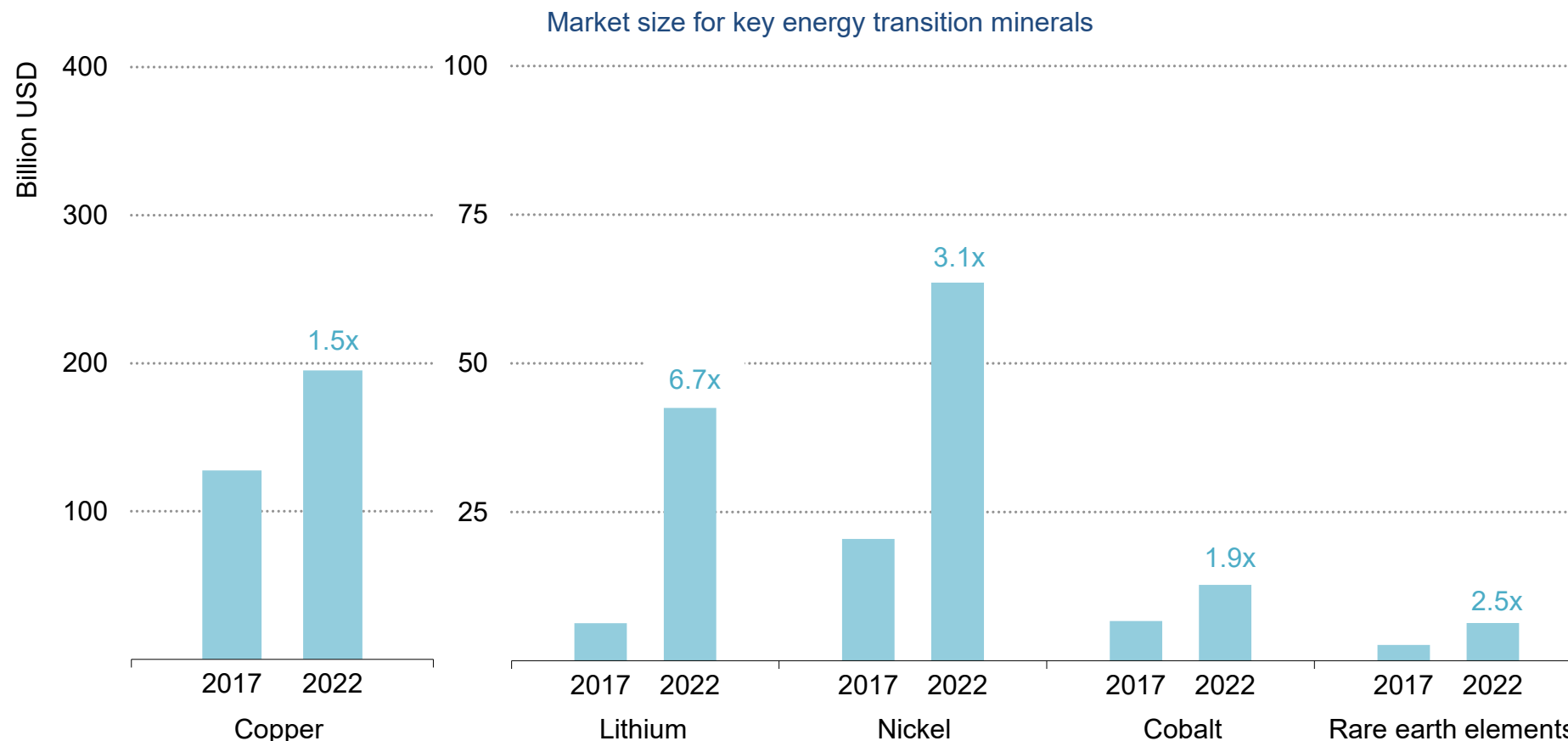
The rapid rise of clean energy has underpinned significant growth in mineral demand

Demand for key materials and share of clean energy in total demand



IEA. CC BY 4.0.

Thanks to heightened demand and rising prices, the market size for energy transition minerals doubled over the past five years, reaching USD 320 billion in 2022



IEA. CC BY 4.0.

Note: The market size for nickel includes both Class 1 (battery grade) and Class 2 nickel.

Source: IEA analysis based on S&P Global.

As clean energy deployment hits new records, energy transition minerals are becoming a major focus for the mining and metals markets

Deployment of clean energy technologies had another record year in 2022. Electric car markets witnessed unprecedented growth as sales exceeded [10 million units](#) in 2022, with a total of 14% of all new cars sold being electric – up from less than 5% in 2020. The People's Republic of China (hereafter, “China”) was the front runner, accounting for around 60% of global electric car sales in 2022, followed by the European Union and the United States. Electric car sales are generally low outside the three major markets, but there are promising signs in some emerging markets such as India and Indonesia. Thanks to the increasing availability of affordable models and strengthened policy support, EV sales are expected to grow strongly through 2023. Over 2.3 million electric cars were sold in the first quarter of 2023, about 25% more than in the same period last year. Alongside the strong growth of EV sales, investment in energy storage systems is growing even faster with a doubling of capacity additions in 2022. Our early estimates suggest another doubling of new installation in 2023, driven by strong growth in utility-scale battery systems.

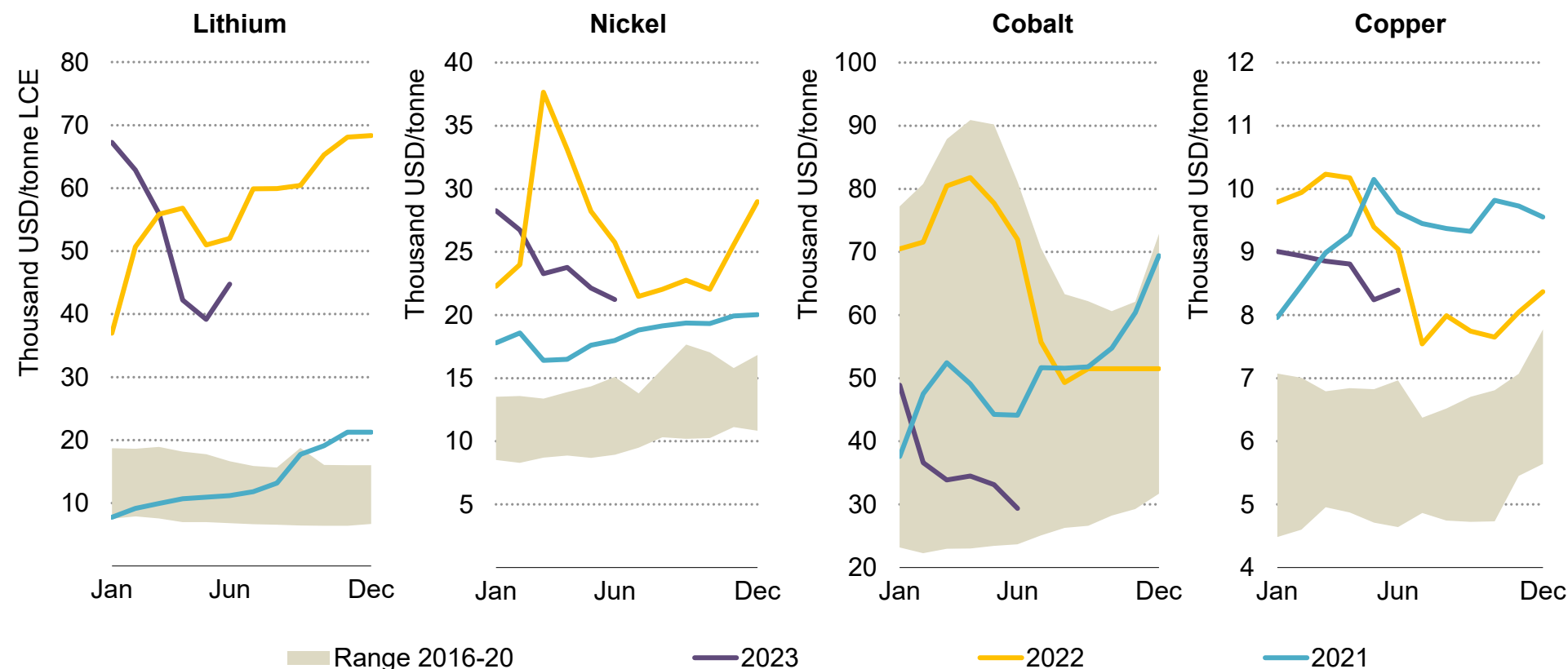
With around 340 GW of capacity addition, global spending on renewables hit a new record at [almost USD 600 billion](#) in 2022, despite cost and supply chain pressures. The growth was mainly driven by solar PV. China alone added almost 100 GW of solar PV capacity in 2022, almost 70% higher than in 2021, and is on track to add [150 GW in 2023](#). The European Union also saw remarkable growth in solar PV additions

that were up by [almost 50%](#) compared with 2021, resulting from the push to ramp up investment in renewables as Europe responds to the cuts in Russian gas deliveries. In 2022, wind capacity did not grow as fast, as the sector was exposed to permitting bottlenecks, schedule delays and margin pressures. However, onshore wind capacity additions are expected to rebound strongly [by 70% in 2023](#) as delayed projects start to come online.

The continuous increase in clean energy deployment in recent years has led to a significant rise in demand for critical minerals. From 2017 to 2022, demand for lithium tripled while nickel and cobalt demand increased by 40 and 70% respectively. Coupled with heightened prices, the market size of key energy transition minerals – namely copper, lithium, nickel, cobalt and graphite – doubled, reaching USD 320 billion in 2022. This contrasts with the relatively modest growth of bulk materials such as zinc and lead. As a result, energy transition minerals, which used to be a small segment of the market, are moving to centre stage in the mining and metals industry. In 2022, the share prices of critical mineral mining companies [outperformed](#) those of the overall mining sector by a wide margin. The clean energy sector has been firmly in the driving seat of this growth. In 2022, the share of clean energy applications in total demand reached 56% for lithium, 40% for cobalt and 16% for nickel, up from 30%, 17% and 6%, respectively, five years ago.

After the surge in 2021 and 2022, many critical mineral prices started to moderate in 2023, but remain well above historical averages

Price development for selected energy transition minerals and metals



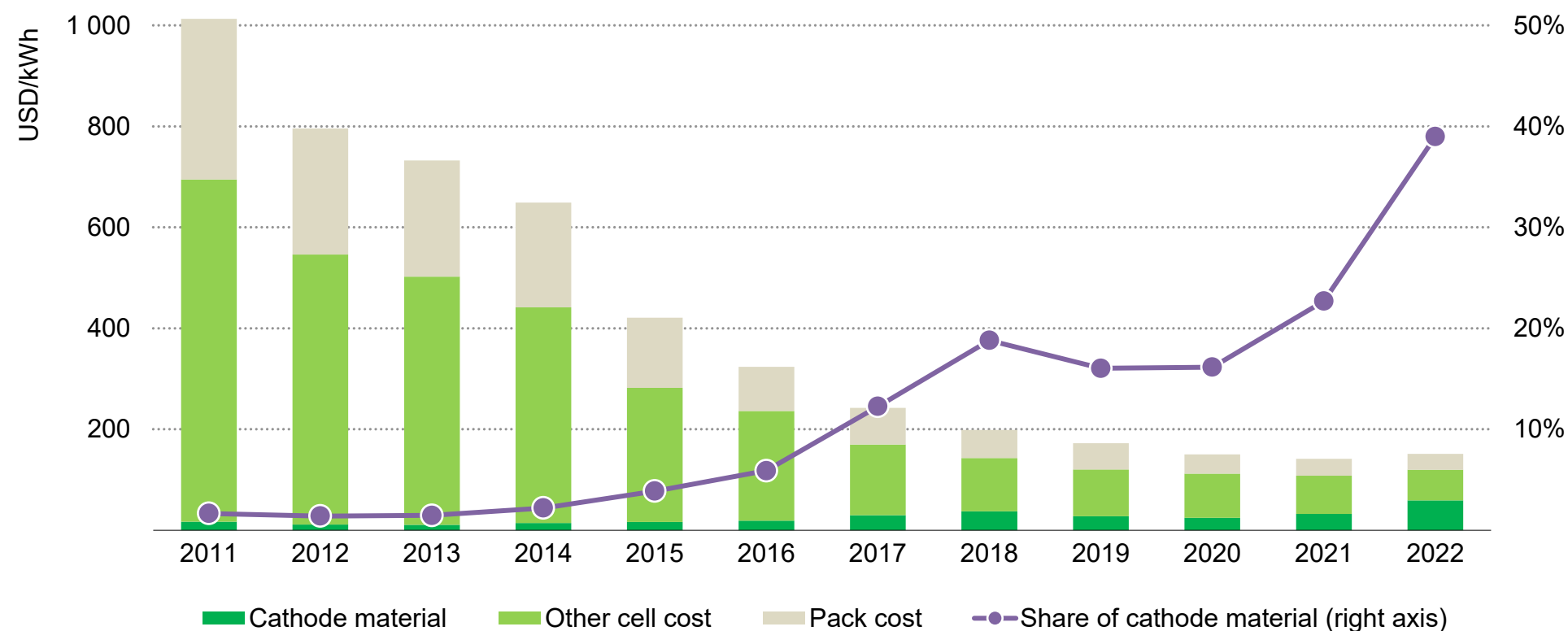
IEA. CC BY 4.0.

Notes: LCE = lithium carbonate equivalent. Assessment based on LME Lithium Carbonate Global Average, LME Nickel Cash, LME Cobalt Cash and LME Copper Grade A Cash prices (nominal).

Source: IEA analysis based on S&P Global.

With elevated commodity prices, raw material costs loom larger in the total cost of key clean energy technologies

Average pack price of lithium-ion batteries and share of cathode material cost

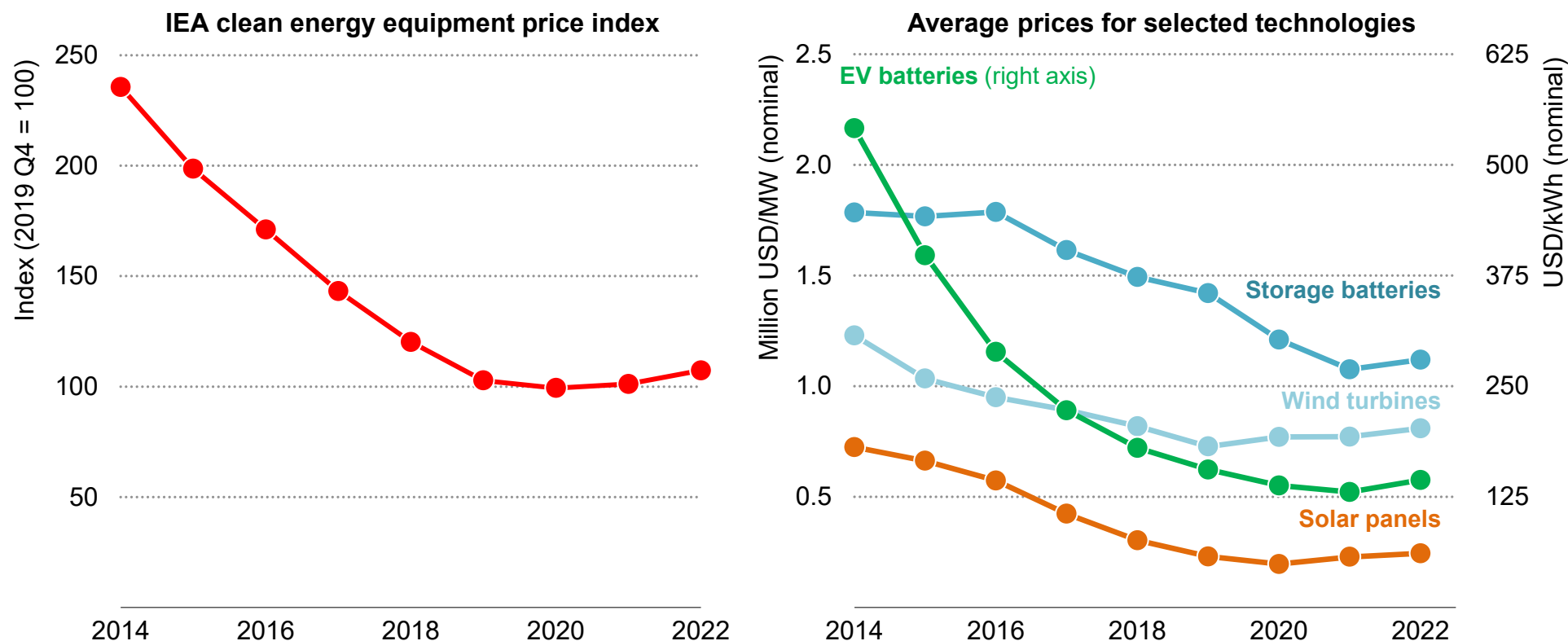


IEA. CC BY 4.0.

Notes: Cathode material costs include lithium, nickel, cobalt and manganese. Other cell costs include costs for anode, electrolytes, separator and other components as well as costs associated with labour, manufacturing and capital depreciation.

Source: IEA analysis based on [BNEF \(2022\)](#).

Clean energy technology prices continued to increase for the second year in a row although the recent price fall for critical mineral inputs could provide some respite



IEA. CC BY 4.0.

Note: The IEA clean energy equipment price index tracks price movements of a fixed basket of solar PV panels, wind turbines and lithium-ion batteries (for EVs and energy storage). Prices are weighted based on the shares of global average annual investment.

Source: IEA analysis on company financial reports, Bloomberg and BNEF.

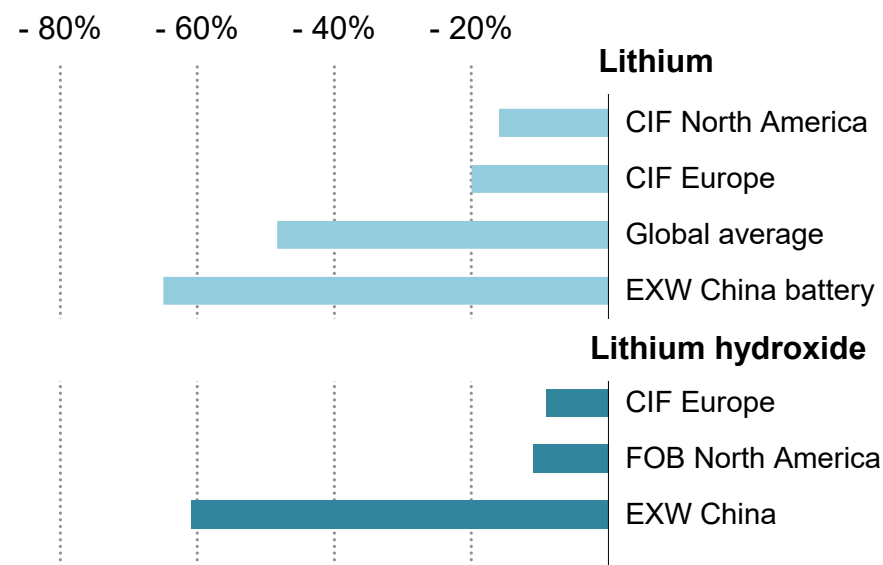
Critical mineral supplies are having a major impact on the affordability of energy transitions

Many critical minerals that are vital for clean energy technologies experienced broad-based price increases in 2021 and early 2022, accompanied by strong volatility and significant peaks, particularly for nickel and lithium. With the exception of lithium, most prices began to moderate in the second half of 2022. Expectations for China's reopening underpinned a brief rally at the end of 2022, but prices resumed their declines in the first few months in 2023, including lithium, on the back of weak consumption, new supply plans and concerns about a possible recession. China's reopening has not yet translated into a revival of industrial activities, as the recovery has been driven mostly by its service sector. Beyond China, across many economies, manufacturing purchasing managers' indices are consistently underperforming their service counterparts, leading to weakness in demand for industrial metals. Further, the reduction in EV subsidies and price cuts for conventional cars in China put additional pressure on prices.

Nonetheless, current prices for most materials remain well above historical averages. Near-term prices may be dampened by the risks of an economic recession, the possible spread of the banking crisis and a planned increase in supplies. However, medium-term prices for many energy transition minerals may remain above historical levels as the economy recovers. Schedule delays or cost overruns remain a nonnegligible possibility for many announced projects, while sustained policy support for clean energy deployment is set to prop up demand. Additionally, supply-side events may induce short-term price pressures,

as seen in early 2023, with mine supply disruptions in Chile and Peru, heavy rainfall in Indonesia and Brazil, and disrupted aluminium production due to hydropower shortages in China.

Changes in lithium prices between January and April 2023
by price index



IEA. CC BY 4.0.

Notes: CIF = cost insurance and freight; FOB = free on board; EXW = Ex Works.

Source: IEA analysis based on S&P Global.

A notable trend in recent months has been the steeper decline in the price index in China compared with other regions. Between January and

April 2023, lithium carbonate prices in China plummeted by over 60% whereas those in Europe dropped by only 20%. This was mostly linked to destocking across the battery supply chain, which lowered apparent demand for lithium while the underlying demand has remained robust. Starting from May 2023, domestic lithium prices in China are showing signs of rebound with growing optimism for a near-term recovery in demand.

Low exchange stock levels are an additional area of concern. From aluminium to copper and to nickel, stock levels in the London Metal Exchange (LME) remain at historic lows, with limited signs of recovery, exacerbated by the recent [event](#) surrounding its registered nickel warehouse in March 2023. This leaves the market vulnerable to supply-side events, geopolitical disruptions or speculative financial activities.

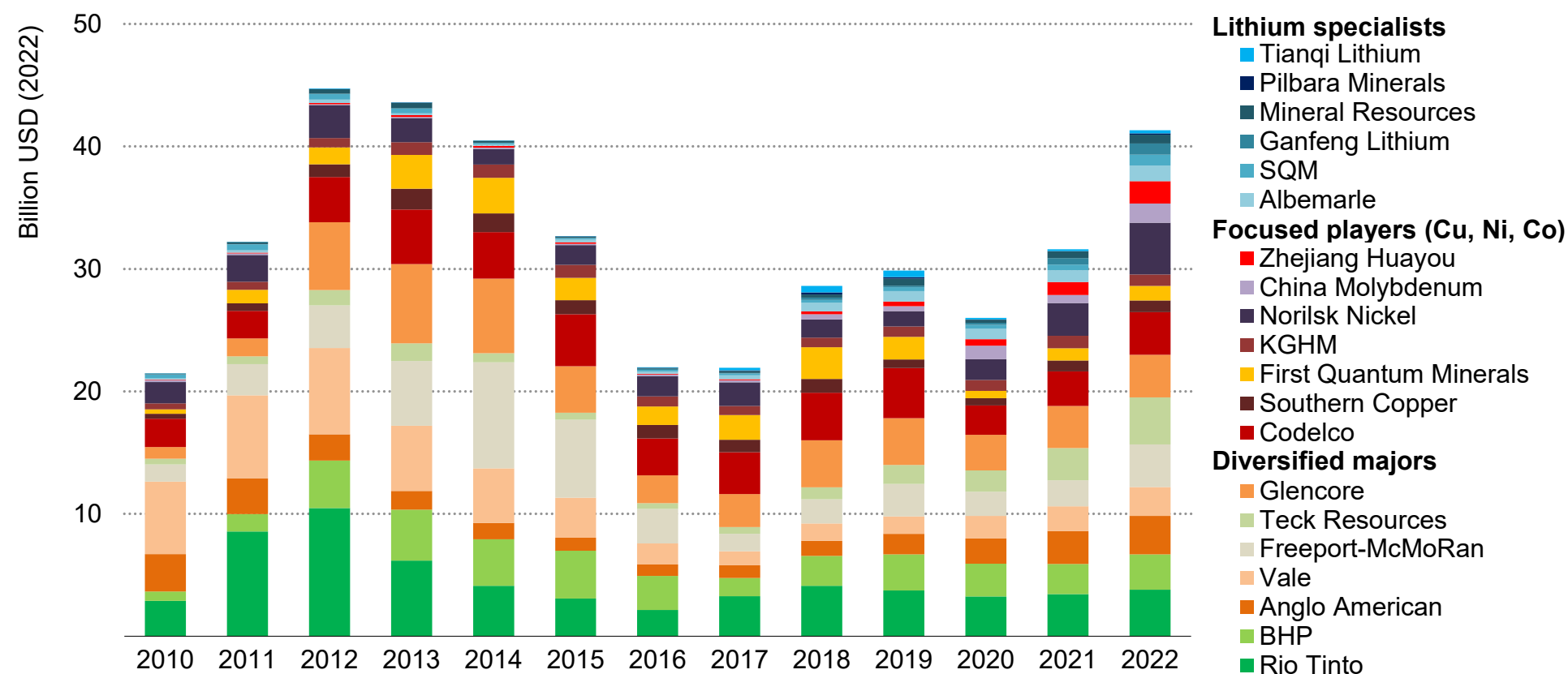
Higher or more volatile mineral prices could have a significant effect on the costs of transforming our energy systems. In the 2010s, technology learning and economies of scale led to a substantial reduction in the costs of key energy technologies. However, this also means that raw material costs now make up a larger share of the total cost of clean energy technologies. For instance, the share of cathode materials in battery costs was under 5% in the middle of the last decade, but it has recently surged to over 20% in 2021 and nearly 40% in 2022. When anode materials and other raw material inputs are added in, the share of raw materials rises further, underscoring the importance of mineral prices in determining the affordability of clean energy technologies.

The IEA's clean energy equipment price index monitors price movements of a representative global basket of clean energy equipment products, including solar PV panels, wind turbines, and lithium-ion batteries for EVs and energy storage. This index declined consistently at an annual average rate of 13% from 2014 until the end of 2020, after which it started to rise. By the second quarter of 2022, the index reached the same value as it had four years earlier. Individual clean energy technology prices have reflected this trend. Prices of wind turbines have risen consistently between 2020 and 2022, although they show some signs of easing in 2023. Prices of solar PV modules increased between 2020 and 2021 for the first time after a decade of declining prices. They continued to rise in 2022, albeit at a slower pace, although 2023 could be the year of relief as silicon prices gradually start declining. Unlike solar and wind, price pressures did not arrive for batteries in 2021, but 2022 became the first year that prices for both storage and EV batteries saw an uptick, reversing a decade of falling costs that had resulted from technology innovation and economies of scale.

Despite these recent setbacks, it is noteworthy that the prices of all clean energy technologies today are significantly lower than a decade ago. As things stand, 2023 could be a crucial year for clean energy technology prices. Whether and how quickly they resume a downward trajectory will depend on the speed of innovation and on the stability of mineral markets that witnessed significant volatility in 2022 after two years of pandemic-related supply chain disruptions followed by the onset of global geopolitical uncertainty.

Investment in critical mineral mining rose by 30% in 2022 as strengthening momentum for energy transitions offers prospects for robust demand growth

Capital expenditure on nonferrous metal production by major mining companies



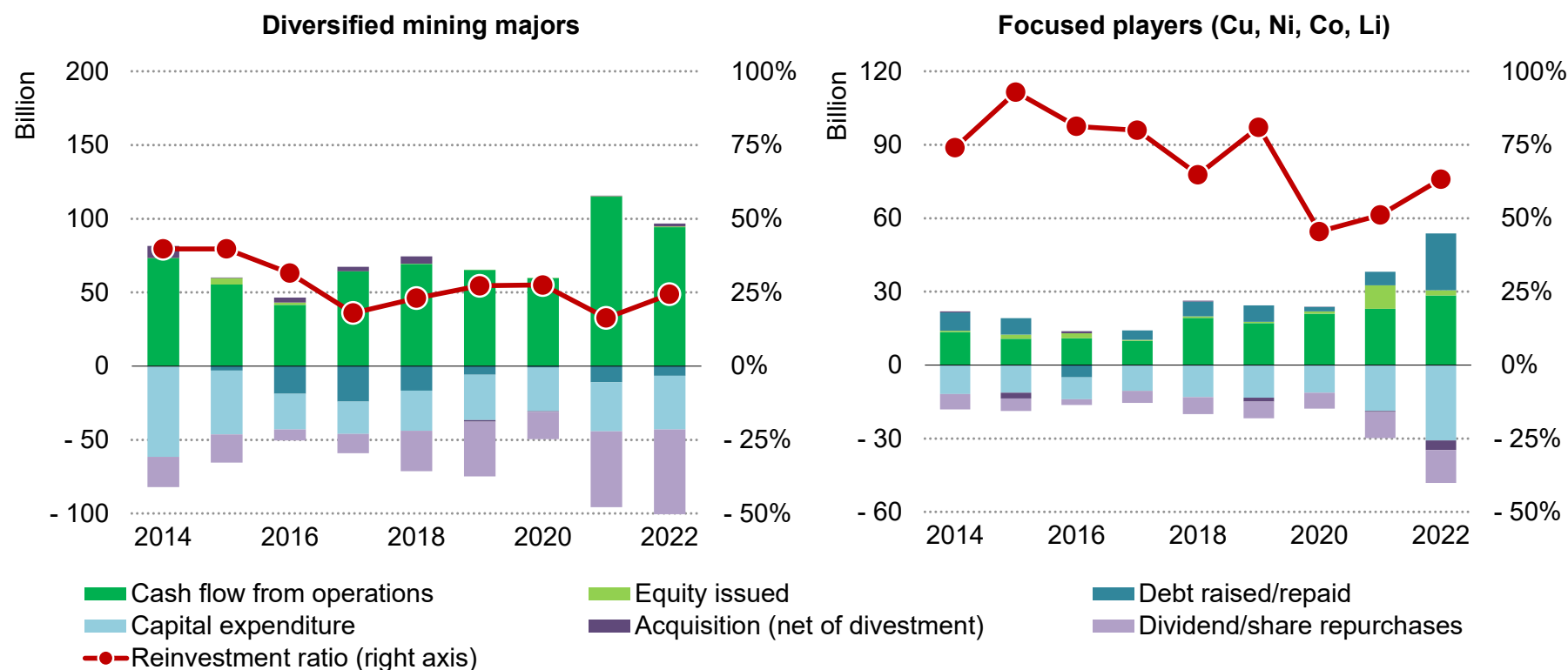
IEA. CC BY 4.0.

Notes: Co = cobalt; Cu = copper; Ni = nickel. For diversified majors, capex on the production of iron ore, coal and other energy products was excluded.

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

Diversified mining majors are taking a more measured approach to investment whereas specialist players are taking more risks in pursuit of future growth

Cash generation and disposition trends by major mining companies



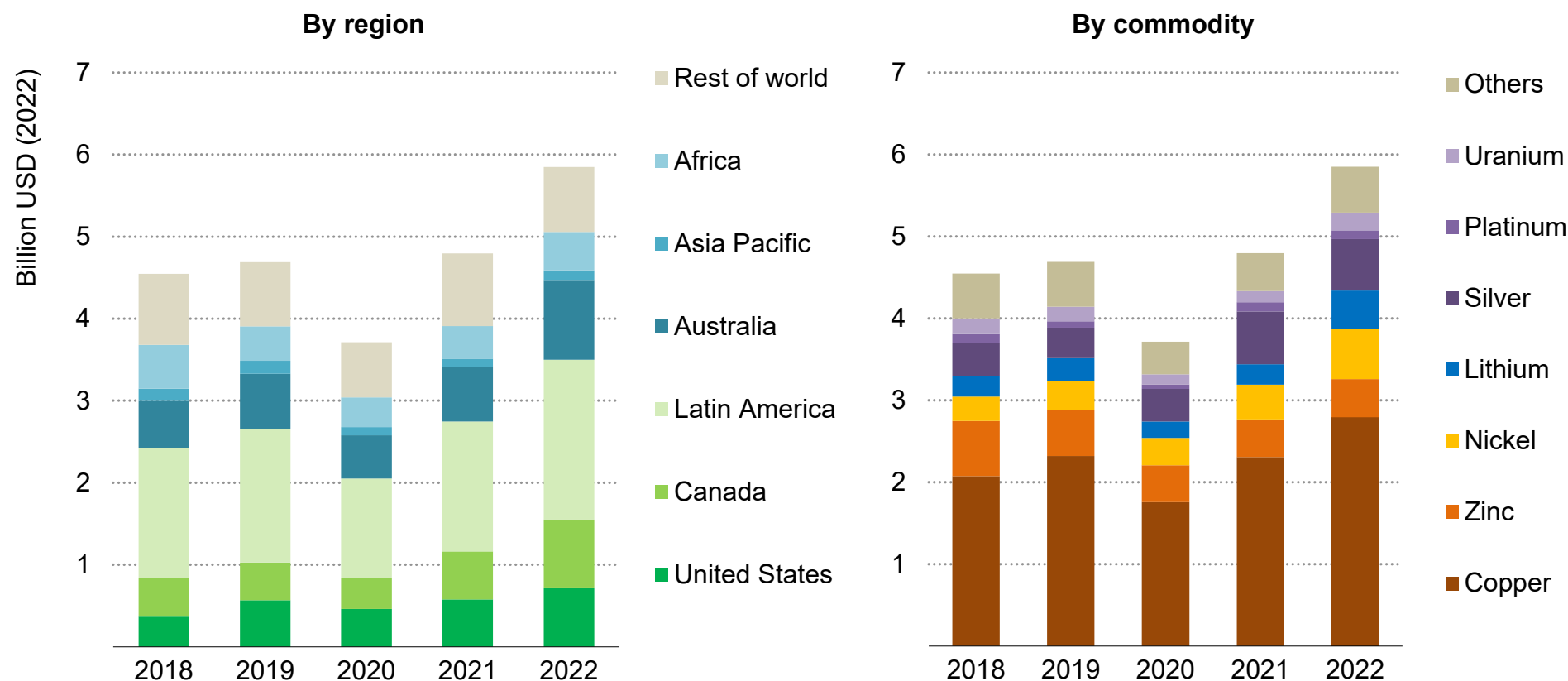
IEA. CC BY 4.0.

Notes: Focused players include "Lithium specialists" and "Focused players (Cu, Ni, Co)" in the previous page. Excludes investment in marketable securities and others. Capital expenditure covers all commodities, including nonferrous metals. Reinvestment ratio investment = capital expenditure in nonferrous metal production as a percentage of operating cash flow.

Source: IEA analysis based on company financial reports.

Exploration spending continued to march upwards, led by Australia and Canada

Exploration spending for selected nonferrous mineral resources



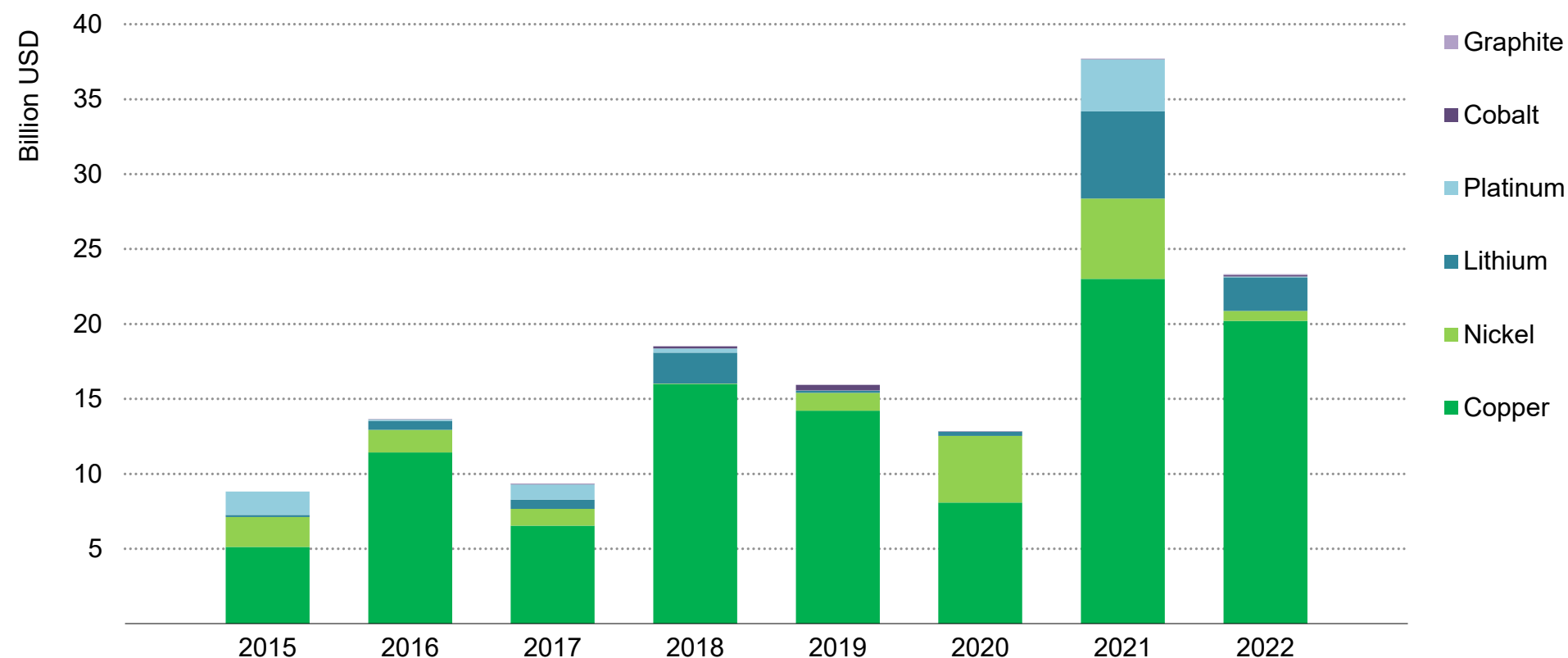
IEA. CC BY 4.0.

Notes: Excludes budgets for iron ore, coal, aluminium, gold and diamonds. Others comprise rare earth elements, potash/phosphate and many other minor metals.

Source: IEA analysis based on S&P Global.

M&A activities for energy transition mineral assets were weaker in 2022 than in 2021, but remain above pre-Covid levels

Announced mining M&A deal values for selected energy transition minerals

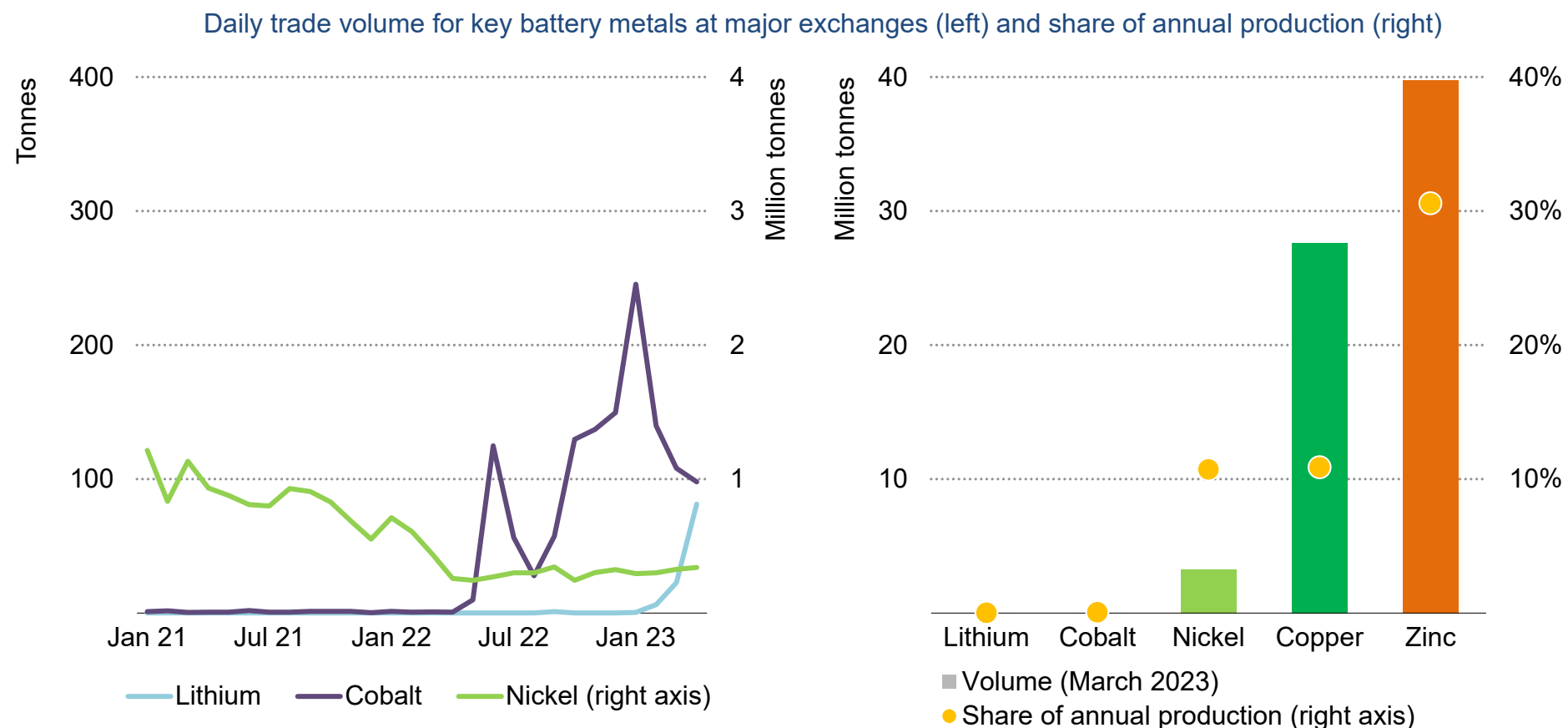


IEA. CC BY 4.0.

Notes: M&A = merger and acquisition. Include both company and property deals over USD 1 million. Streaming, royalty-related and earn-in transactions are excluded.

Source: IEA analysis based on S&P Global.

Trading liquidity for battery metals at major exchanges started to pick up, but has significant scope for further deepening



IEA. CC BY 4.0.

Note: Cobalt (Chicago Mercantile Exchange [CME], LME), lithium (CME, LME), nickel (LME, Shanghai Futures Exchange [SHFE]), copper (CME, LME, SHFE), zinc (LME, SHFE).

Source: IEA analysis based on Bloomberg.

Strong cash flows and the momentum behind energy transitions are driving growth in investment and exploration spending

Thanks to high commodity prices, the mining industry had another strong year in 2022, which resulted in elevated profitability and cash flows. In addition, growing policy support to diversify critical mineral supply chains prompted many mining companies to increase their investment in critical minerals development. We have assessed the aggregate investment levels of 20 large mining companies that have a significant presence in developing minerals essential for the energy transition. The list includes diversified mining majors and specialised developers for specific energy transition minerals such as copper, nickel, cobalt and lithium. Following the 20% increase in 2021, investment spending recorded another sharp uptick by 30% in 2022. Companies specialising in lithium development recorded a 50% increase in spending, followed by those focusing on copper and nickel developments. Companies based in China nearly doubled their investment spending in 2022.

Exploration spending also continued its upward march in 2022, up by 20%, driven primarily by record growth in lithium exploration, followed by copper and nickel. Canada and Australia led the way with over 40% growth year-on-year, notably in hard-rock lithium plays, thanks to favourable policy support such as Canada's [Critical Mineral Exploration Tax Credit](#) that was introduced in 2022. Exploration activities are also expanding in Africa and Brazil. In contrast, exploration spending in the Russian Federation (hereafter, "Russia") decreased by 30% as a result

of international sanctions and boycotts by individual explorers. China also saw a 10% decline in exploration spending due to Covid-19 related restrictions.

In terms of commodities, lithium emerged as the clear leader in exploration activities, with spending increasing by 90%, following a 25% increase in 2021. Uranium also experienced a significant increase in spending, rising by 60% due to renewed interest in nuclear power amid concerns over Russian supplies. Nickel was a close follower with a 45% growth rate for exploration, led by Canada where high-grade sulphide resources, proximity to existing infrastructure and access to low-emissions electricity create attractive investment opportunities.

Strong cash flows in 2021 and 2022 have enabled the mining industry to allocate a greater amount of capital to new developments, exploration, and mergers and acquisitions (M&As), while the remaining surplus has been returned to shareholders and creditors through dividends, share buybacks and debt repayment. Based on the assessment of 20 companies' cash generation and disposition patterns, approximately 50% of the capital was allocated to investment while around 50% was returned to investors and lenders. Following the dip in 2020 and 2021, the industry's reinvestment ratio, calculated by dividing nonferrous metal investment by operating cash flows, returned to pre-Covid levels in 2022. There is a notable difference among company types. Diversified mining

majority in general were more cautious in their growth investment, with the reinvestment ratio edging up only slightly.

However, specialised players focusing on energy transition minerals increased investment by over 40% and allocated a greater portion to growth investment, buoyed by an increase in profits. In this segment, a change in financing patterns was observed, with a shift from debt funding, which had been the primary source of financing prior to 2020, to equity funding since 2021. This shift reflects the industry's growing desire for further expansion as well as investors' improved sentiment towards the critical minerals sector.

At over USD 20 billion, M&A transactions related to energy transition minerals were lower in 2022 than in 2021, when they rebounded strongly from the dip in 2020. Copper remained as a dominant focus of M&A activities. [Rio Tinto's acquisition of Turquoise Hill Resources](#) (USD 3.1 billion), which included Mongolia's Oyu Tolgoi mine, was a notable example. [BHP's acquisition of OZ Minerals](#) (USD 6.4 billion), which was completed in May 2023, was another example. Beyond copper, lithium-related acquisition rose from USD 0.3 billion in 2020 to USD 5.8 billion 2021 before declining to USD 2.2 billion in 2022. [Rio Tinto's USD 825 million purchase of the Rincon Lithium Project](#) from Sentient Equity Partners underscores the growing importance of lithium as a focus of M&A activities. Nickel-related mining acquisition was minimal in 2022 although there was a major deal in the refining sector – [the acquisition of the Yabulu refinery in Australia](#) by the Zero Carbon Investek consortium (USD 1.3 billion). This transaction is not included in

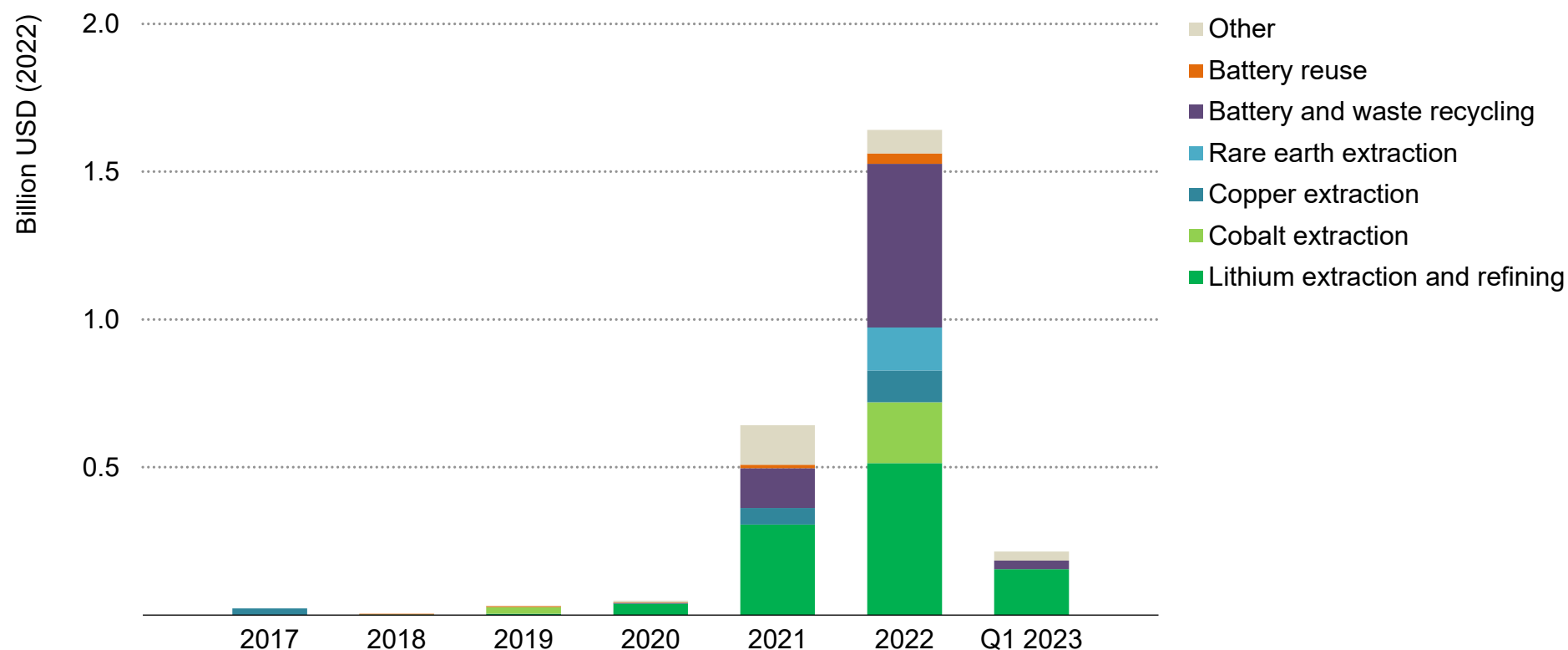
our analysis, which focused on mining M&A activities. Despite the modest fall in 2022, M&A activities remain robust in the first half of 2023, especially for lithium assets, with the [mega-merger between Livent and Allkem](#) being a prime example (USD 10.6 billion).

As investment into the sector grows, trading liquidity for battery metals has notably improved since 2022. Unlike base metals, battery metals such as lithium and cobalt have traditionally been traded based on bilateral multiyear contracts, with limited activity on major exchanges such as the LME, the CME, and the SHFE. However, early signs indicate this is beginning to change. Cobalt trading volumes, which were zero at the end of June 2022, skyrocketed to over 500 lots (tonnes) by the end of 2022, peaking at 1 300 lots on 17 January 2023. Lithium trading volumes have also been on the rise, albeit at a slower pace, reaching 276 lots by April 2023. Conversely, nickel trading has continued to trend downwards, indicating that the sector has not fully restored [stakeholders' confidence](#).

This highlights the growing importance of spot pricing and the potential emergence of financial instruments to hedge price risks. However, the trading liquidity of battery metals still lags significantly behind that of other bulk materials, despite recent improvements. As it stands, daily traded volume as a percentage of annual production represents less than 1% for lithium and cobalt, compared with 10-30% for major materials such as nickel, zinc and copper. This underscores significant potential to increase market liquidity as well as the need to enhance market transparency as the sector continues to grow.

Despite headwinds in the wider venture capital sector, critical minerals start-ups raised a record USD 1.6 billion in 2022

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



IEA. CC BY 4.0.

Source: IEA analysis based on Cleantech Group (2023).

Investors are backing start-ups with new processes to break into critical mineral supply chains

With technical, regulatory and political developments all pointing to a large future market for critical minerals, innovators with new techniques for extracting and processing them have been able to attract funds for testing and scale-up. In 2022, despite a dip in overall venture capital (VC) funding for technology entrepreneurs, critical minerals start-ups raised record amounts of equity, reaching USD 1.6 billion, of which USD 0.25 billion was for higher risk early-stage ventures. This 160% year-on-year increase took the critical minerals category to 4% of all VC funding for clean energy in that year.

The first quarter of 2023 has been strong for critical minerals, despite a severe downturn in other VC segments, such as digital start-ups. Investments so far in 2023 put critical minerals on track to overtake 2021 levels by the year's end, and beat 2022 for early-stage deal value alone. The momentum for critical minerals start-ups in 2023 indicates that investors expect the policy environment to enable new projects to reach financial close, with a significant share going to the unconventional mineral resources in which small entrepreneurs are most active.

Reaching a market size of more than one billion dollars is particularly impressive given that no critical mineral companies raised “growth-stage” funds between 2016 and 2020. Growth-stage companies require more capital for capital-intensive scale-up, but while they still do not typically generate profits yet, this innovation stage is less technically risky than early-stage, which funds initial ideas, business creation and

prototyping. Growth-stage funding for critical minerals firms in 2022 rose 160% from its 2021 level, to USD 1.4 billion.

While the overall trend is limited to a relatively small sample of companies (159 deals for 87 companies in total since 2010), the data reveal a clear response to market signals, strategic priorities and announced government funding. Whereas the only deals in this segment prior to 2017 were in the areas of copper, silicon and rare earth elements, in 2022 the largest category was battery recycling. For example, Green Li-ion, a Singaporean start-up, received USD 35 million of funding in 2022 to 2023, including from an electric utility and an oil and gas company. The next largest category was lithium extraction and refining, epitomised by Energy Exploration Technologies, a Puerto Rican company developing direct lithium extraction methods, received USD 500 million in 2022 to 2023, including from General Motors, a car company.

Regionally, companies based in the United States raised most of the funds, at 45% of the total between 2018 and 2022. In particular, US start-ups raised most money in battery recycling and lithium extraction, as well as cobalt and magnesium recovery. Canadian and Chinese start-ups are notably active in battery recycling and lithium refining. European start-ups have been successful at raising money for rare earth elements, battery reuse and battery material supply.

Countries are seeking to diversify mineral supplies with a wave of new policies

In response to the pressing need to ensure secure mineral supplies, there has been a proliferation of policy initiatives over the past few years, including landmark measures such as the European Union's [battery regulation](#) and [Critical Raw Materials \(CRM\) Act](#), the US's [Inflation Reduction Act \(IRA\)](#), Australia's [Critical Minerals Strategy](#) and Canada's [Critical Minerals Strategy](#), among others. The IEA [Critical Minerals Policy Tracker](#) has identified nearly 200 policies and regulations from 25 countries and regions worldwide, with over 100 of these enacted in just the past few years. Although countries approach the issue with different goals, there is growing recognition that policy intervention is needed to ensure adequate and sustainable mineral supplies to meet the needs of the energy transition.

The majority of these initiatives share a common objective: to diversify the current supply chains, which are highly concentrated. These efforts aim to mark a departure from the currently dominant commodity supply model, where raw materials are extracted from resource-rich nations in developing economies, processed in China and then shipped to consuming nations as refined metals. Countries are taking different approaches to achieve this goal, often influenced by the position of countries within the supply chain. For example, many countries with large underexploited mineral resources are focusing on developing their domestic production and expanding their value chains. Consuming nations place more emphasis on security mechanisms, refining capacity, technology innovation and recycling. Nonetheless, the promotion of

sustainable and responsible practices in critical minerals supply chains remains a common component of many policy approaches.

Mining policies

In response to the projected increase in demand for critical minerals, policy makers, particularly those in resource-rich countries, are reassessing their legal frameworks for mining. This involves providing support for exploration, such as Canada's 30% [Critical Mineral Exploration Tax Credit](#). In nations that are traditional suppliers of critical minerals, there is ongoing modernisation of mining policies to address environmental concerns and foster stakeholder participation. For example, the Chilean government released its new [National Mining Policy](#) framework in January 2022, which was the result of two years of collaboration involving representatives from private companies, academia and civil society.

Many countries are striving to capture more value from the extraction of their natural resources. For example, Mexico nationalised its lithium industry in 2022, and there are ongoing reforms in Chile related to copper mining royalties, as well as a proposed revision of the lithium concession system, with an increased role given to a state-owned player.

Interventions are extending to other parts of the value chain. Among resource-rich countries, Indonesia has [banned](#) the export of nickel ore

to nurture its midstream value chain, with [a potential export ban](#) being considered for bauxite, tin and cobalt. [Namibia](#) and [Zimbabwe](#) is following similar [strategies](#) with an export ban of all unbeneficiated mineral ore. [A recent study by the OECD](#) shows that export restrictions on critical raw materials have seen a fivefold increase since 2009.

Nations that rely on imports are also reviewing the competitiveness of their mining policies to enhance their self-sufficiency in critical minerals while upholding environmental safeguards. This entails identifying strategic projects and streamlining processes, such as the establishment of “one-stop-shop” permits or reducing permit delays, as proposed in the EU CRM Act.

Public support and tax credits for critical mineral projects

To overcome the Covid19 pandemic, many governments introduced investment programmes aimed at energy transitions, which often included critical minerals as part of the package. In the United States, as part of the [Infrastructure Investment and Jobs Act](#) signed in 2021, the Department of Energy is implementing a USD 6 billion grant programme, half of which is intended to fund domestic production of materials needed for the EV supply chain, including the refining of nickel, lithium, cobalt and rare earth elements (REEs). The other half is allocated for battery manufacturing and recycling. The IRA [introduced](#) a USD 7 500 credit for the acquisition of a clean vehicle under the condition that a large portion of critical minerals are sourced from the United States or a country sharing a free trade agreement with the United States, and that most of the battery components are manufactured in North America. Since the

enactment of the IRA, [over USD 45 billion of investments](#) have been announced for battery supply chain projects, ranging from mineral extraction to battery manufacturing. Australia also released an investment strategy with the Modern Manufacturing Initiative, which provides [funding](#) of AUD 120 million (Australian dollars) for the development of nickel and cobalt refineries, AUD 15 million for REE processing and AUD 6 million for lithium hydroxide. Canada released its first [Critical Minerals Strategy](#) in December 2022, backed by CAD 3.8 billion (Canadian dollars) support. The new [Clean Technology Manufacturing Tax Credit](#) was also introduced to support investments in critical mineral extraction, recycling and processing. As part of the France 2030 investment programme, France has announced EUR 1 billion in public support to critical mineral projects, half in loans and grants (including [five projects](#) selected in 2022) and half invested into a dedicated public-private equity investment [fund](#).

In addition to mining and processing projects, there is also support for R&D activities. The European Union’s [Horizon Europe](#) programme, with an overall budget of EUR 95.5 billion, funds research and innovation in strategic value chains. Examples include EIT RawMaterials, a body that [supports](#) start-ups and innovative projects related to raw materials, and the [RawMatCop programme](#) which uses earth observation data from the Copernicus satellite system to assist in the exploration and monitoring of mining sites. Canada introduced the Critical Minerals Research, Development and Demonstration (CMRDD) programme, which has supported [six pilot and demonstration projects](#) in the field of nickel, lithium and REEs, with CAD 14.1 million so far.

Supply security

A growing number of countries that rely on critical minerals imports have introduced policies to enhance supply security. The IEA is also developing a voluntary critical mineral security programme with its member countries to enhance preparedness against potential disruptions. As a first step, most policies aim to increase understanding of potential risks. Many nations have recently updated their critical mineral lists and strategies in light of the evolving market context. For example, Canada updated its list in 2021, the United Kingdom in 2022, and the European Commission and the United States in 2023. Some countries have also strengthened their market intelligence functions to gain better insights into the market. Examples include France's [Observatory of mineral resources for industrial clusters](#) (OFREMI), the United Kingdom's [Critical Mineral Intelligence Centre](#), and Canada's [Critical Minerals Center of Excellence](#). In the CRM Act, the European Commission has proposed EU-wide supply monitoring and stress tests, mandatory information sharing among EU member states, and risk preparedness exercises for large downstream manufacturers.

Some jurisdictions have been using regulatory tools to secure supply and support alternative sourcing strategies. These can involve public procurement rules, as well as national agencies coordinating procurement, offtake agreements, and stockpiling. Japan and Korea have such agencies and have been operating stockpiling systems. The European Commission's CRM Act includes proposals around stockpile coordination, common purchasing and support for offtakes.

International cooperation

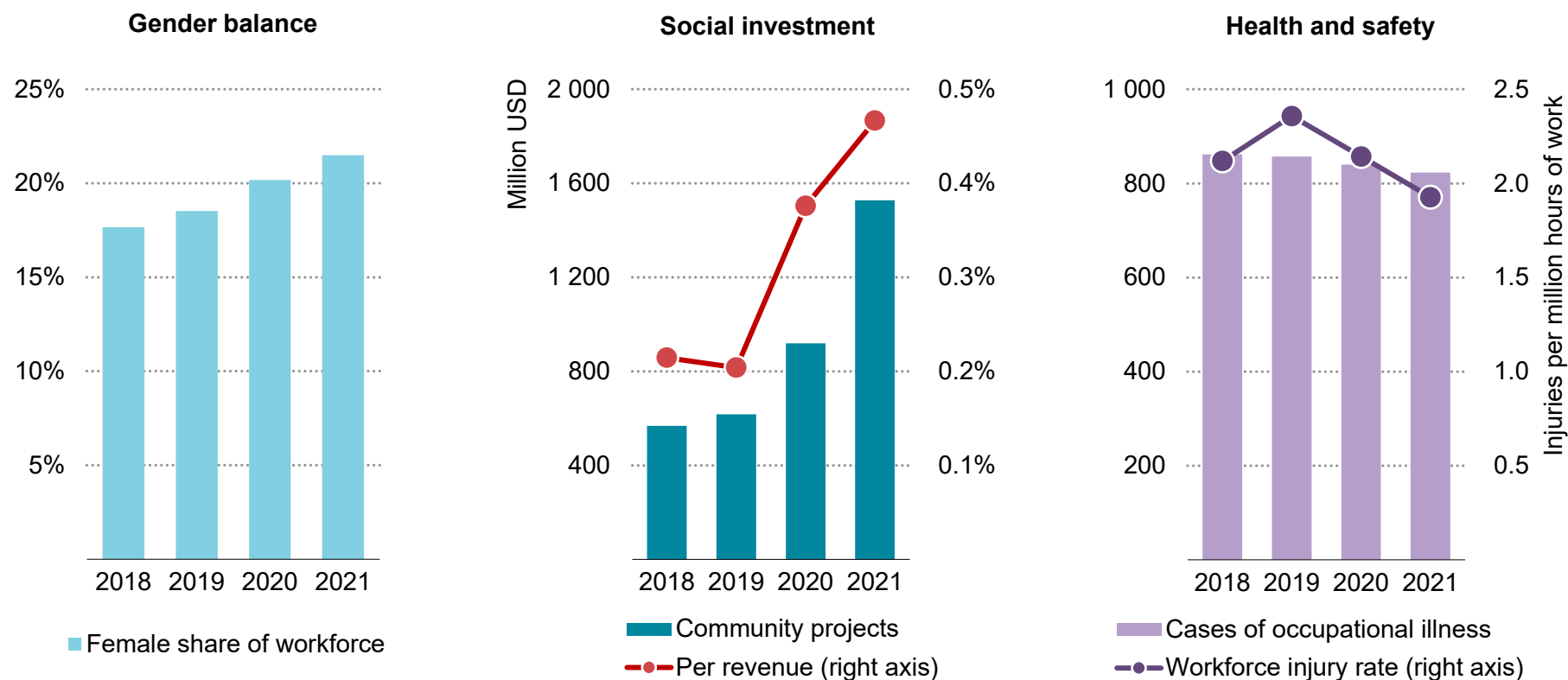
International cooperation on critical minerals is rapidly developing to ensure reliable mineral supplies. There have been numerous bilateral agreements, alongside multinational cooperations, to co-develop critical mineral projects and ensure improved access to mineral supplies. The US IRA gives priority to materials sourced domestically or from partner countries, creating a context for an acceleration of bilateral trade agreements. The United States and Japan recently [signed](#) a trade agreement specifically centered on critical minerals, and further bilateral trade agreements with the European Union are under negotiation. The [Mineral Security Partnership](#), launched by the United States and key partner countries, aims to facilitate cross-investment in new mines and processing facilities in diversified regions.

Environmental, social and governance policies

Nearly all countries enforce environmental standards in their domestic markets through permitting and other conditions. There are several efforts to incorporate due diligence requirements directly into their regulatory frameworks with an aim to enhance supply chain transparency and encourage responsible sourcing. The [EU battery regulation](#), for example, requires importers and manufacturers to track the country of origin of the raw materials used in batteries. Policies aimed at increasing the scale of recycling are also gaining traction. Recent policies involve recycling rate targets, information disclosure requirements about material composition and “recycled content” obligations for new products.

There are some signs that environmental, social and governance practices are improving in mining operations...

Gender, social, health and safety indicators for selected mining companies



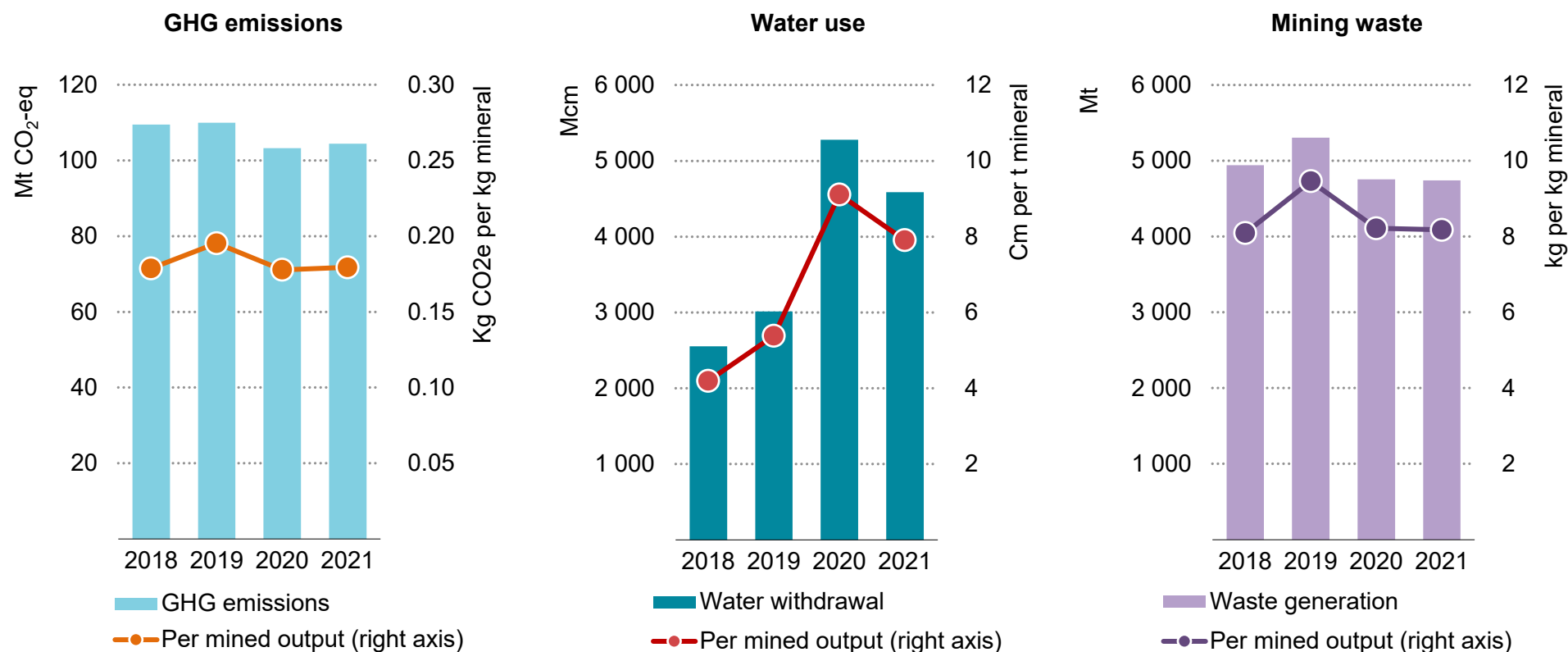
IEA. CC BY 4.0.

Notes: Aggregated data for Albemarle, Anglo American, BHP, CMOC, Codelco, First Quantum Minerals, Freeport-McMoRan, Ganfeng Lithium, Glencore, Mineral Resources, Norilsk Nickel, Rio Tinto, SQM, Teck Resources and Tianqi Lithium. Considers reported data for all operations. Gender balance and injury rate indicators show the weighted average by production.

Source: IEA analysis based on company reports.

...but many areas still lack industry-wide progress, especially in environmental sustainability

Environmental indicators for selected mining companies



IEA. CC BY 4.0.

Notes: CO₂-eq = carbon dioxide equivalent. Aggregated data for Albemarle, Anglo American, BHP, CMOC (only for GHG emissions), Codelco (only for GHG emissions and water use), First Quantum Minerals, Freeport-McMoRan, Ganfeng Lithium (only for GHG emissions and waste), Glencore, Mineral Resources, Norilsk Nickel, Rio Tinto, SQM (only for GHG emissions and waste), Teck Resources, and Tianqi Lithium. Considers reported data for all operations.

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

Is the industry making progress on ESG?

The mining industry has been associated with a host of negative environmental, social and governance (ESG) impacts, including human rights violations, contribution to armed conflict, [environmental contamination](#), deforestation and other harms. Failure to manage these impacts could have [profound implications](#) for clean energy transitions as well as damage the environment and communities in the vicinity of mining deposits.

There are indications that companies are stepping up actions to reduce or eliminate environmental and social harms associated with their activities. Some of the largest mining companies – including [BHP](#), [Glencore](#), [Rio Tinto](#), [Vale](#) and others – have committed to achieve net zero emissions by 2050 across their operations, to improve public disclosures of ESG-related information, to promote diverse and inclusive workforces, and to reduce occupational injuries.

Major industry players publish sustainability metrics on GHG emissions, worker health and safety, and other ESG aspects through annual sustainability reports. These reports can broaden the public availability of information on mining performance beyond occupational safety and GHG emissions to include data on water use, land footprint and recovered areas, waste generation, air pollutants, gender balance, community engagement and other topics.

However, there are limitations on what is publicly available. Reported data are usually aggregated at company level, combining information

from different mineral resources across various regions. Apart from a few companies that are mostly dedicated to critical minerals, metrics are often dominated by high-volume commodities such as iron ore and coal. Also, while many operators follow the Global Reporting Initiative Standards, the choice of scope and criteria varies substantially. There are some companies that do not report on sustainability at all.

Meanwhile, investors are increasingly concerned with ESG performance, recognising it is closely tied to supply and reputational risks. ESG performance is affecting access to capital and its cost, paving the way for the potential emergence of green premiums. However, many stakeholders are challenged by the multiplicity of standards and ratings alongside obscure company reporting. Different initiatives address particular concerns associated with certain minerals or parts of the supply chain, but it is not necessarily easy to assess ESG performance across companies.

To demonstrate their performance, some operators are adhering to site-level sustainability standards verified by third parties such as [Towards Sustainable Mining](#) (TSM) and the [Initiative for Responsible Mining Assurance](#) (IRMA). Both initiatives have seen growing uptake in recent years. TSM was created by the Mining Association of Canada, but now has participating organisations in over ten countries, including Argentina, Australia and Brazil. IRMA has completed audits at more than a dozen sites in Africa, North America and South America – rating operations against metrics spanning the entire range of ESG

considerations, including human rights, worker safety and health, community and stakeholder engagement, air and water pollution, and water management.

The IEA conducted an initial assessment of company progress across various ESG dimensions based on the public sustainability reports published by 20 major mining companies that have a strong presence in energy transition minerals. It revealed a mixed picture for progress on different ESG dimensions. These companies have made headway on community investment, worker safety and gender balance. However, there are many areas where progress has been much slower, especially on environmental sustainability. GHG emissions remain at high levels, with roughly the same amount being emitted per tonne of mineral output every year. Water withdrawals almost doubled from 2018 to 2021. During the same period, waste generation oscillated around 5 Gt, with 2021 intensities slightly above 2018 levels.

Reporting varies substantially in both consistency and breadth. Some companies provide very granular reporting, across several years, with data for hundreds of categories and detailed regional information. Others provide only highlights on an aggregate level, covering only a handful of areas. Altogether, over all the ESG dimensions reviewed during this assessment, only a handful were disclosed by more than 15 companies. Total energy consumption and scope 1 and 2 GHG emissions were the most reported categories. Due diligence checks, fatalities and waste recycling were some of the categories with the lowest level of disclosure.

The industry as a whole will face increasing pressure to provide detailed, transparent and granular information that allows stakeholders to fully understand its performance, compare it across commodities and companies, and track progress over time. Many customers are aiming to trace impacts across the entire life cycle of products, including mineral inputs and related operations. ESG credentials may soon be required on a product basis through traceability systems, product or battery passports.

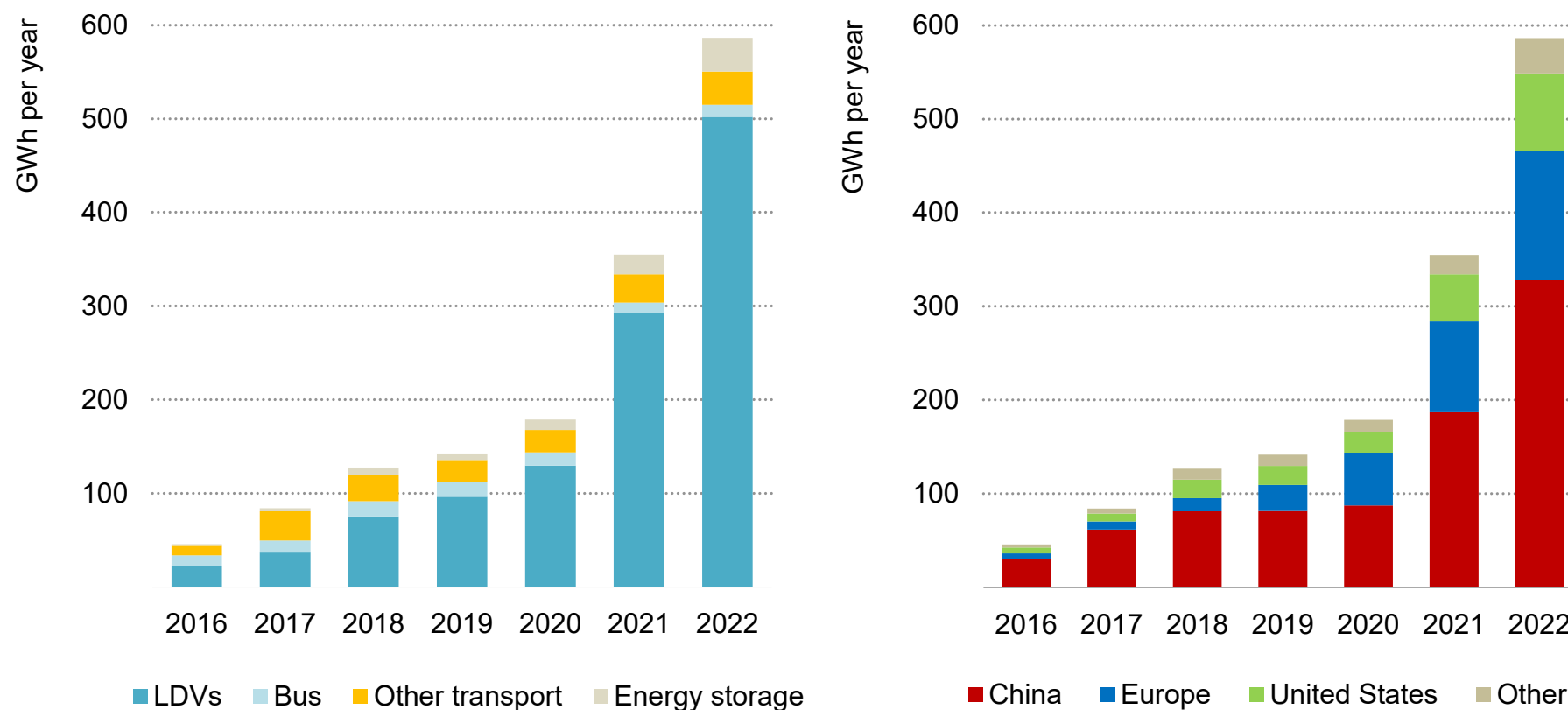
The uptake of such systems will depend on how ESG affects supply agreements. There is a question mark regarding the extent to which ESG factors are being seriously considered in consumers' sourcing and investment decisions, beyond the mining industry.

Different production pathways have varying degrees of environmental impact. For instance, the production of battery-grade nickel from laterite resources by converting nickel pig iron to matte is several times more energy-intensive than the production route based on sulphide resources. Additionally, synthetic graphite anodes have higher emissions than natural graphite anodes. However, despite the availability of cleaner production pathways, the [Battery Materials Review](#) suggests that end users and investors are not necessarily prioritising them in their sourcing and investment decisions, although some battery manufacturers started to track emissions associated with their supply chain, giving preference to minerals with a lower climate impact.

Developments in the battery sector

Global battery demand for clean energy applications increased by two-thirds in 2022, mainly for transport but with power sector storage growing fast

Battery demand in the clean energy sector by segment and region



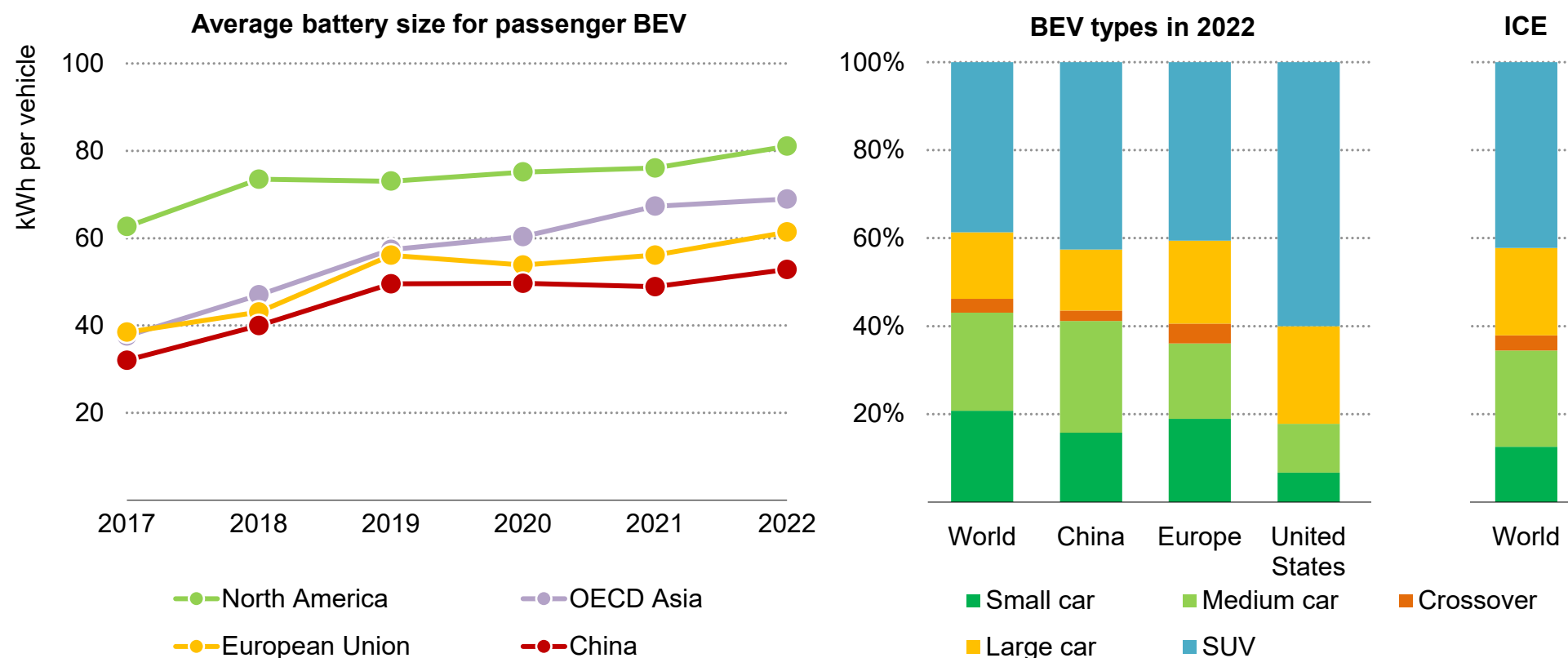
IEA. CC BY 4.0.

Notes: LDVs = light-duty vehicles, including cars and vans. Energy storage includes both utility-scale and behind-the-metre storage. In the left chart, Other transport includes medium- and heavy-duty trucks and two-/three-wheelers.

Source: IEA (2023), [Global EV Outlook 2023](#).

A consumer preference for bigger conventional cars is being replicated in the EV sector, pushing up the average size of batteries

Developments of average battery size in key regions (left) and car model availability by segment (right)



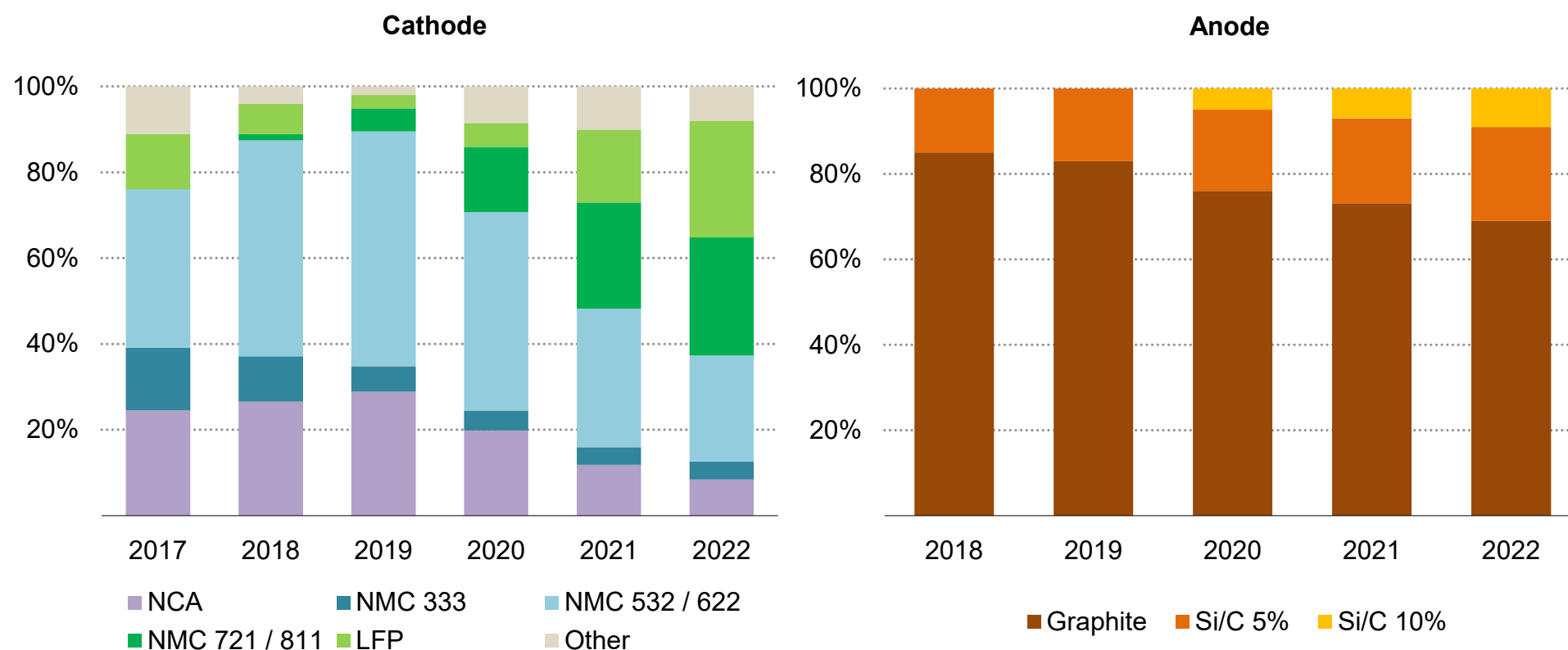
IEA. CC BY 4.0.

Note: BEV = battery electric vehicle; ICE = internal combustion engine. In the right-hand chart, distribution is based on the number of available models, not sales-weighted.

Source: IEA (2023), [Global EV Outlook 2023](#).

Cathode chemistry choices are bifurcating towards high-nickel or LFP while anode chemistries see a growing adoption of silicon-doped graphite

Evolution of sales shares for EV batteries (cars) by cathode and anode chemistry, 2018-2022



IEA. CC BY 4.0.

Notes: LFP = lithium iron phosphate; NCA = nickel cobalt aluminium; NMC = nickel manganese cobalt. Si/C refers to silicon-graphite anodes, with the silicon doping ratio alongside.

Source: IEA analysis based on data from EV Volumes, Benchmark Minerals Intelligence and BNEF.

Global battery demand for transport and energy storage had a record year, while chemistries evolved in an attempt to accommodate the effects of volatile mineral prices

In 2022, demand for lithium-ion batteries in the automotive sector increased by around [65% to reach 550 GWh](#), up from 330 GWh in 2021. This stemmed primarily from the growth in electric passenger car sales, with new registrations in 2022 being 55% higher than the previous year. In the People's Republic of China (hereafter, "China"), battery demand for vehicles grew by more than 70% in 2022 as electric car sales rose rapidly. Battery demand in the United States grew by around 80% during the same year, despite electric cars sales only increasing around 55% relative to 2021. This was due to the average battery size of electric cars in the United States being 40% higher than the global average, mainly because of the relatively [higher share of SUVs](#) in the country compared with other major markets.

However, the growing appetite for lithium-ion batteries in 2022 was not limited to EVs. The battery energy storage market also experienced remarkable growth, with the market size nearly doubling to 80 GWh (combined for utility-scale and behind-the-meter), marking one of the largest annual increases in deployment ever witnessed in this sector. This burgeoning demand has led automakers to follow in the footsteps of the trend pioneered by Tesla's Powerwall and directly enter the battery energy storage market. In 2022, General Motors and Toyota launched behind-the-meter energy storage products.

Apart from the growing sales of EVs, the increasing battery size is also a key factor driving demand growth for batteries and, in turn, for critical minerals. The IEA has been raising the question of how the [growing consumer preference for larger cars](#) will impact future emissions from the transport sector. The average battery size for passenger electric cars has been on an almost unbroken rising trend for many years in nearly every major market. While more EV models become available on the market, there is visible evidence that the trend of favouring larger vehicles seen in conventional car markets is [being replicated in the EV market](#) as automakers seek higher profits and consumers opt for larger cars, often beyond what they need. If this trend persists, it will impose additional pressure on battery supply chains and further increase demand for the critical minerals required to make the batteries.

Battery chemistry trends have shown some major developments since 2019. Cathode chemistries have demonstrated a visible bifurcation in the past few years. On the one hand, nickel manganese cobalt (NMC) chemistries with high cobalt content (or low nickel content) such as NMC 333 (also referred to as NMC 111) are being phased out in favour of NMC 721, NMC 811 (high-nickel/low-cobalt) and even lower cobalt-content chemistries. On the other hand, the affordable and safe but less energy-dense lithium-iron phosphate chemistry (LFP) has been making a decisive comeback and steadily increasing its market shares thanks to strong support from local and global (Tesla) automakers in China,

leading to renewed interest in the chemistry from automakers in the West as well. Volkswagen's plans to produce entry-level models in Europe with LFP batteries and Ford's decision to build an LFP battery manufacturing plant in the United States significantly advance production capacity of the chemistry outside China in the coming years. Both the NMC and LFP developments have close links to the critical minerals that are needed for the production of batteries: while reducing cobalt content has been a decades-long endeavour for companies aiming to reduce costs and mitigate social risks for battery manufacturing, the rise of LFP is triggered by the fact that, rather than three or more, this variant uses just one key critical battery mineral, namely lithium, reducing concerns around critical mineral supplies (albeit not completely, see Box 1).

On the anode side of developments, graphite remains the dominant choice but the market share of graphite doped with silicon, which

improves its capacity (depending on the quantity of silicon), has been witnessing a steady increase since 2018, reaching around 30% of the market share in 2022.

Taking steps in a completely different and promising direction, sodium-ion batteries, which rely primarily on the abundant element of sodium and avoid the use of almost any critical minerals in sizeable amounts, witnessed a leap forward in early 2023 with the world's largest battery manufacturer, Contemporary Amperex Technology Co., Limited (CATL), and the largest EV maker, BYD, betting on this technology. Nevertheless, with the advantages in energy density and economies of scale that lithium-ion batteries currently have, it remains to be seen how quickly and to what extent sodium-ion batteries can replace lithium-ion batteries (see Box 2).

Box 1. Does the resurgence of LFP imply a more secure future for global battery markets?

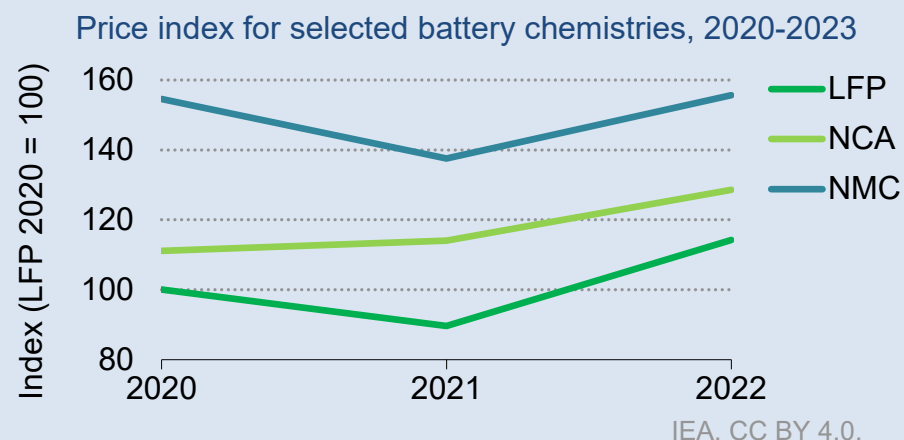
LFP batteries contrast with other chemistries in their use of iron and phosphorus instead of the more critical nickel, manganese and cobalt found in NCA and NMC variants of lithium-ion batteries. The downside of LFP is that their energy density tends to be significantly lower than that of NMC and NCA chemistries although the gap has narrowed noticeably with the cell-to-pack design. In general, an increase in the market share of LFP batteries, as we are witnessing today, implies lower levels of mineral security concerns due to the absence of cobalt, nickel and manganese whose supply chains are more geographically concentrated and prone to disruptions.

Nevertheless, this does not mean that LFP batteries are free from supply chain concerns. LFP batteries contain phosphorus, which is also used in large volumes for fertiliser production. Depending on the evolution of the LFP market share for EVs, the possibility of conflicting demands for phosphorus may arise in the future between battery manufacturing and the agriculture sector.

Furthermore, significant regional imbalances could also arise in the phosphorus supply chain, with possible bottlenecks both in terms of identified resources and processing. [Around 70%](#) of known resources of phosphate rock are geographically concentrated in Morocco and the Western Sahara region. On the processing side, currently the high

purity phosphorus needed for LFP batteries can be produced only by one method with the refining capacities existing in only four countries - China, the United States, Kazakhstan and Viet Nam. Some junior miners are exploring new deposits in [Canada](#) and [Norway](#).

A final consideration is the price. While it is the cheapest variant of a lithium-ion battery, the increase in lithium prices in 2022 caused a larger relative jump in LFP battery prices in comparison with other chemistries. The price hike for LFP was estimated to be [around 25% compared with less than 15% for NMC batteries](#). LFP batteries remain far less expensive than NCA and NMC per kilowatt-hour but the price developments of last year show that the race between different battery chemistries is far from over.



Source: IEA analysis based on BNEF.

EV makers are becoming serious about critical mineral supplies; there has been a notable pick-up in strategic investment into the raw material sector since 2021

Top 10 EV makers' involvement in the raw material supply chain

Market player	Long-term offtake			Investment in mining			Investment in refining		
	Lithium	Nickel	Others	Lithium	Nickel	Others	Lithium	Nickel	Others
BYD				○ ○			○ ○		
Tesla	○ ○	○ ○	○ ○				○		
VW Group	○ ○				○	○		○	
General Motors	○	○	○	○				○	○
Stellantis	○	○	○	○	○	○			
Hyundai			○						
BMW	○ ○		○				○		
Geely Auto									
RNM Alliance	○ ○		○		○	○			
Mercedes-Benz	○								

Notes: VW = Volkswagen. Top 10 EV makers accounted for around 70% market share in 2022. ○ = before 2021; ○ = after 2021.

Source: IEA analysis based on company announcements and news articles.

EV battery cell makers are following the same pathway; top players increased their raw material investments significantly in recent years

Top 7 battery cell makers' involvement in the raw material supply chain

Market player	Long-term offtake			Investment in mining			Investment in refining		
	Lithium	Nickel	Others	Lithium	Nickel	Others	Lithium	Nickel	Others
CATL				○ ○	○	○	○ ○	○ ○	○ ○
LGES	○ ○	○	○	○			○	○ ○	○
BYD				○ ○			○ ○		
Panasonic	○	○	○ ○						
SK On	○	○	○	○				○	
Samsung SDI		○ ○	○						
CALB									

Notes: Top 7 cellmakers accounted for 86% of market share in 2022. ○ = before 2021; ○ = after 2021.

Source: IEA analysis based on company announcements and news articles.

Long-term offtakes became integral for EV cell manufacturers and OEMs' sourcing strategy, but many players are taking an extra step by investing in the critical minerals value chain

In recent years, there has been a noticeable mismatch in the pace of developments within the EV supply chain. On the manufacturing front, the industry is witnessing a surge in announcements to build new battery gigafactories. When all the announced projects are summed up, they get close to the required scale in the IEA Net Zero Emissions by 2050 Scenario, which achieves net zero emissions globally by 2050. Although “announced” does not mean that all these projects will come to fruition, this trend is an encouraging sign of progress towards climate goals. However, the expected pace of growth in mineral supplies does not match that of manufacturing capacity additions for EV batteries. This has led to concerns among automakers, battery cell makers and equipment manufacturers about securing raw material supplies, prompting major market players to explore different financial and sourcing strategies to secure mineral supplies.

Worries about security of supply tend to push industry procurement strategies towards long-term offtake agreements – binding agreements to purchase a certain quantity of critical minerals over an extended period. Tesla's major long-term offtakes include a five-year contract with [Australia's Lontown Resources](#) to source lithium spodumene concentrate, starting 100 000 tonnes in 2024 and growing to 150 000 tonnes in subsequent years, and a five-year contract with [nickel processing companies in Indonesia](#) worth USD 5 billion. General Motors inked a long-term offtake contract to receive 25 000 tonnes of battery

grade nickel sulphate annually from [Vale Canada](#) starting from the second half 2026. BMW Group also signed a USD 335 million offtake deal with US-based [Livent](#) to source lithium hydroxide in Australia. Renault has a seven-year deal with [Managem Group](#) to annually source 5,000 tonnes of cobalt sulphate from Morocco and a five-year deal with [Vulcan Energy](#) to source 6 000 tonnes to 17 000 tonnes of lithium annually.

While long-term offtake continues to play an important role, a recent investment trend shows EV OEMs and battery cell manufacturers taking an extra step to invest in part of the critical minerals value chain such as mining, refining, precursor materials and cathode production, especially from around 2021. These movements are underpinned by expectations that acquiring a stake would enable a stronger control over the critical minerals supply, help safeguard their production pipeline and mitigate exposure to market risks in the longer term.

CATL, the largest battery cell maker in China, has made the acquisition of critical mineral assets a central element of its strategy. For instance, CATL's second-largest shareholder, Sichuan CATL, acquired a 25% stake worth USD 3.7 billion in [CMOC](#), the second-largest cobalt producer in the Democratic Republic of the Congo. A CATL-led consortium also won a bid to develop [lithium reserves in Bolivia](#), with a plan to invest over USD 1 billion in the project's first phase.

Other market players' acquisitions have been mostly in the mining segment of critical minerals which saw a sharp rise since 2021. LG Chemical, a parent company of LG Energy Solution, currently holds a 5.7% stake of [Piedmont Lithium](#). BYD is negotiating the acquisition of [six unnamed lithium mines in Africa](#) containing more than 25 Mt of ore grading 2.5% lithium oxide. SK On is set to acquire a 10% stake in [Lake Resources](#), an Australian lithium developer, with the rights to secure up to 230,000 tonnes for ten years starting from the fourth quarter of 2024. General Motors announced a new investment of USD 650 million in [Lithium Americas](#) to develop Nevada's Thacker Pass lithium mining project. Stellantis acquired a 8% stake worth USD 52 million in [Vulcan Energy](#), an Australian-German lithium startup, and extended its previous five-year offtake deal to ten years.

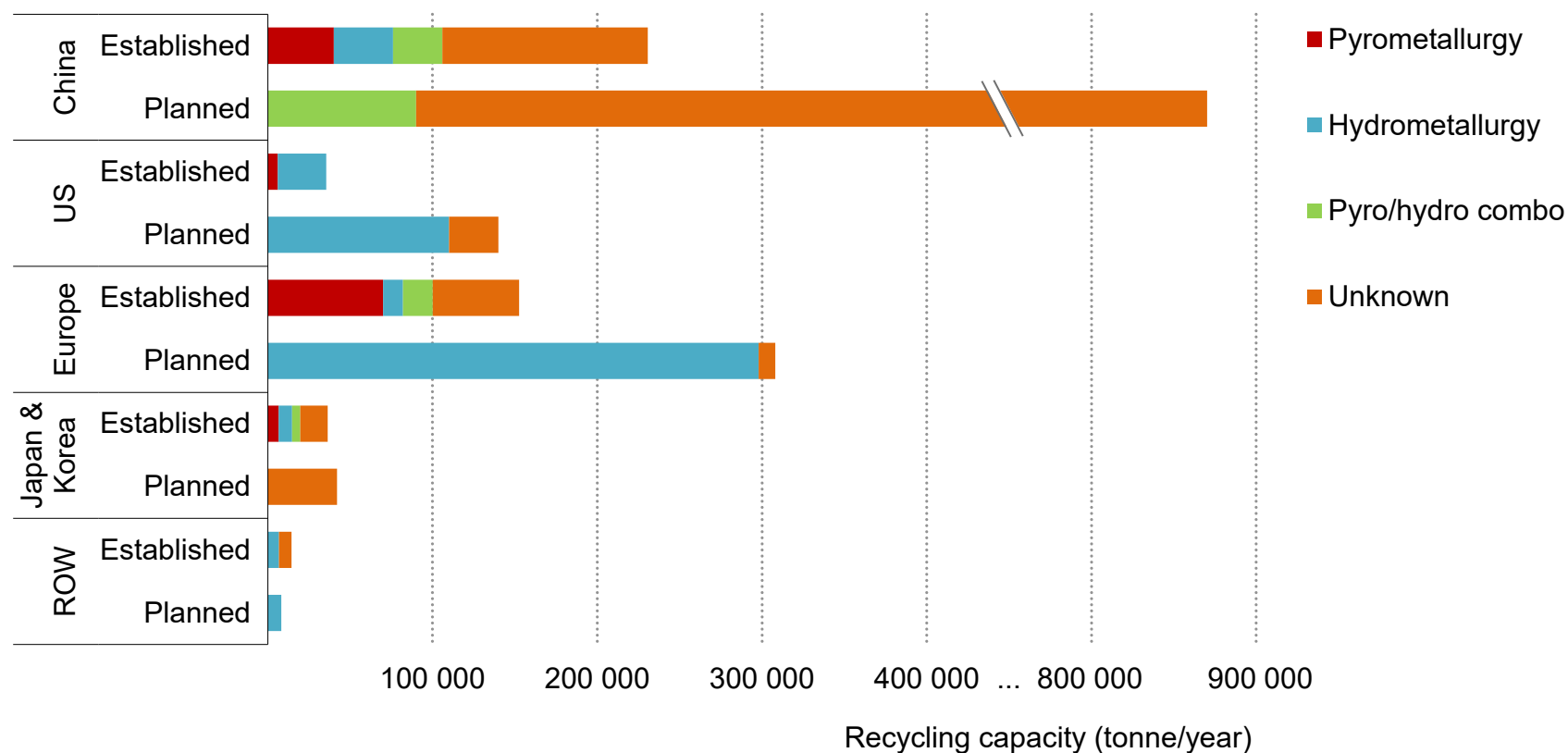
While the scale of investment is greater in the mining sector, investment in refineries also increased in recent years. Tesla announced a plan to

build a new lithium hydroxide refinery on the [Texas Gulf Coast](#) in October 2022. Volkswagen Group announced its plan to build a nickel ore production and processing plant [in Indonesia](#) in July 2022.

Investment in the overall lifecycle of the EV value chain has also been emerging. A unit of CATL is set to join [local state-owned groups in Indonesia](#) to build USD 6 billion mining-to-batteries complex which will include nickel mining and processing, battery materials, recycling, and battery manufacturing facilities. A consortium led by LG Energy Solution, the world's second largest EV battery maker, announced plans to invest [USD 9 billion in the entire EV battery value chain](#) in Indonesia, including smelting and refining of nickel, and manufacturing cathode materials. In Canada, General Motors, BASF, POSCO and Vale aim to [develop a battery hub](#) in Bécancour, Quebec, including raw materials, cathode and recycling operations.

A significant amount of battery recycling capacity is being developed mainly in China, Europe and the United States

Established and planned battery recycling capacity by recycling technology and region, 2023



IEA. CC BY 4.0.

Notes: ROW = rest of world. Based on 53 identified battery recycling projects.

Source: IEA analysis based on Baum et al. (2022), [Lithium-Ion Battery Recycling - Overview of Techniques and Trends](#), BNEF and company announcements.

Scrap from manufacturing processes is dominating today's recycling pool, but this is set to change by the end of the decade

Recycling of lithium-ion batteries is still in its nascent stages. Today, the vast majority of recycling capacity is located in China, which is also home to the largest EV fleet and battery manufacturing capacity in the world. At an estimated 230 kt per year, the established recycling capacity in China is 1.5 times larger than the combined capacity in Europe. Batteries being recycled today are predominantly coming from consumer electronics and battery manufacturing scrap. Until there are sufficient quantities of batteries to recycle at the end of life, scrap from manufacturing processes is set to play an important role. However, this is expected to change dramatically as almost 150 GWh of used EV batteries will reach the end of their first life by 2030.

Some of the largest recycling facilities already in operation include the German company Redux which has a recycling [capacity](#) of 50 kt per year and [achieves](#) a metal recycling rate of 95% and the Guangdong Brup Group in China which has a battery recycling [capacity](#) of 30 kt per year with a recovery rate over 99% for nickel and 97% for cobalt and manganese. In 2023, Glencore and Li-Cycle [announced a plan](#) to study the feasibility of developing a large battery recycling hub in Europe. Most established battery recycling operations rely on pyrometallurgy, but the majority of the planned capacity uses either hydrometallurgy or a mix of the two because hydrometallurgy is less energy-intensive and allows for higher recovery rate.

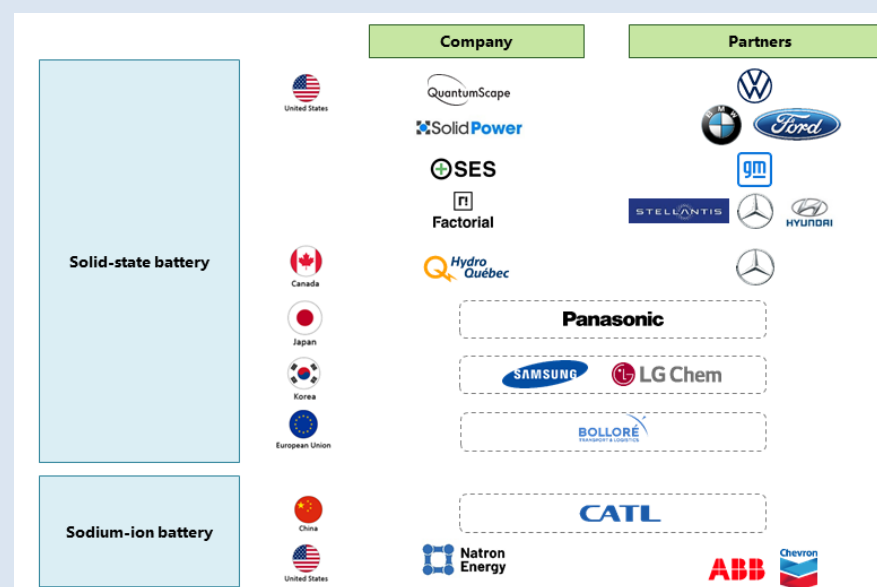
Despite progress in some key regions, efforts for recycling need to be scaled up significantly in the coming years, particularly in Europe and North America where the deployment of EVs is the largest outside of China. Europe is estimated to represent around 15% of global scrap pool in 2030 according to [Benchmark Mineral Intelligence](#). For this, further policy support to incentivise recycling, standardise battery design with recycling in mind and formulate regulations for the movement of end-of-life EV batteries is needed. China, Europe and the United States have all recently taken new policy steps in this area. In China, the Ministry of Industry and Information Technology issued the Interim Measures for the *Management of Recycling and Utilisation of Power Batteries and New Energy Vehicles* whereby manufacturers would have the responsibility to close the loop for batteries. In the United States, the states of California and Washington have recently [passed bills](#) for battery recycling and in the European Union, the new [Critical Raw Materials Act](#) requires 15% of annual consumption to be from recycled sources by 2030. Going beyond the role of policies, OEMs are increasingly considering vertical integration of the car manufacturing and recycling processes or collaborating with recycling companies at the early stage of the planning processes. To facilitate such cooperation, the Global Battery Alliance is [testing](#) the prototype for a battery passport to assist in the tracking and proper management of batteries.

Box 2. New batteries on the horizon?

As global EV sales and deployment of variable renewables set new records each year, innovation in lithium-ion batteries has evolved and improved more rapidly in the past decade than some of the industry's most ambitious expectations. However, achieving global climate goals requires a further improvement in battery performance to bring better and cheaper batteries to the market. Several promising developments are underway. Academic and corporate laboratories are hunting for ways to improve the technology – boosting volumetric and gravimetric energy density, speeding charging time, targeting material efficiency and substitution, enhancing safety and cutting costs. Several new technologies could see progress in 2023, though they will likely take longer to gain significant market shares.

Sodium-ion batteries made quite a ripple in early 2023. These batteries have a design similar to that of conventional lithium-ion batteries, including a liquid electrolyte, but instead of relying on lithium, they use sodium as the main conducting element. They may not improve energy density but they could cut costs significantly because they rely on cheaper, less-critical materials than lithium-ion batteries. The iEVA50 by the Chinese company HiNA (a JAC-Volkswagen joint venture) became the first sodium-ion battery equipped electric car. It will be [followed](#) by two other Chinese cars: CATL and the Seagull by BYD, with mass production slated to start in 2023 in both cases.

Examples of companies working on and investing in R&D for solid-state and sodium-ion batteries as of April 2023



IEA. CC BY 4.0.

Note: Non-exhaustive based on a representation of interest in novel battery technologies.

Source: IEA analysis based on company announcements.

But for sodium-ion batteries to truly compete, it needs to be seen if they will be able to meet the needs for EV range and charging time, which is why several companies are targeting less demanding applications to start, such as stationary storage or micromobility. Despite these

limitations, plans to produce sodium-ion batteries are picking up with [over 100 GWh](#) of production capacity in the pipeline, mostly in China.

Even within the standard lithium-ion battery class, the resurgence of improved LFP cathodes (LFP 2.0) may have a break-out year in 2023, further penetrating the light duty vehicle segment that was previously biased towards the more energy-dense NMC and NCA chemistries. Recent improvements in LFP chemistry and manufacturing have helped boost the performance of these batteries, and companies are moving to adopt the technology. LFP market share is growing quickly, from under 10% of the global EV market in 2018 to almost 30% according to various estimates in 2022. Tesla is already using LFP batteries in some models and regions, and automakers such as Ford and Volkswagen announced that they plan to start offering some EV models with the chemistry too. Furthermore, the advent of a lithium manganese iron phosphate variant of the LFP battery could provide even [higher density](#) than conventional LFP, with mass production expected to start in 2024.

Until recently, battery technology development has focused mostly on the cathode but improvement is also made on anodes. The energy density and charging speeds of graphite anodes have been significantly boosted by doping the graphite anode with silicon. The startup OneD Battery Sciences working on state-of-the-art silicon-graphite blended anodes has partnered with General Motors and Sionix Energy and aims to bring them to market in 2023.

Solid-state batteries go even further by switching the traditional graphite anodes to lithium metal anodes or pure silicon, which could significantly enhance energy density and thermal safety. These anodes have significantly higher charge collection capacity than graphite and makes the anode much thinner to improve energy density, while the solid electrolyte improves thermal stability over the liquid electrolytes in incumbent technologies. Companies such as QuantumScape, Solid Power, Factorial Energy, Bolloré, Panasonic, Samsung, ProLogium, and Hydro Québec are surging ahead in their development with auto giants such as Volkswagen, BMW, Ford, General Motors, Stellantis and Hyundai betting strongly on them.

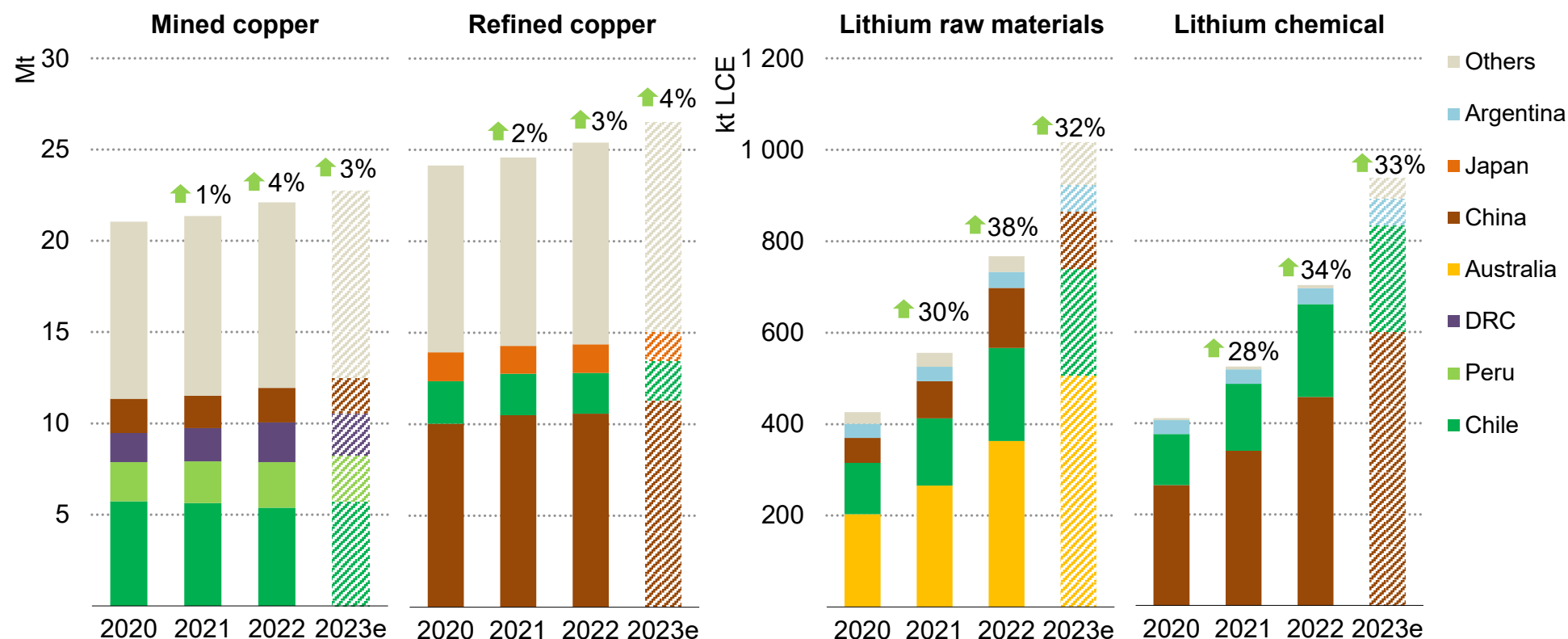
In the long-term, lithium-sulphur batteries offer the potential to diverge completely from all commercial chemistries to date, pushing the boundaries of currently available energy densities and even surpassing the improvements of the solid-state battery. While these innovations could usher in a new era for battery compactness, EV range and charging times, significant technological hurdles need to be overcome for this technology to scale up.

Nonetheless, rapid changes in battery chemistries could prove challenging for the recycling industry as there would be a need for constant adaptation. Furthermore, the use of lower-value materials as in LFP or sodium-ion batteries could potentially lower the monetary incentive to recycle these batteries without strong policy support.

Key trends by individual commodity

Copper production is starting to grow after flat years, but medium-term risks remain; lithium supply is continuing its strong upward journey

Production trends for copper and lithium



IEA. CC BY 4.0.

Notes: LCE = lithium carbonate equivalent. DRC = Democratic Republic of the Congo.

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

Trends for copper and lithium

Copper

Since the second half of 2022, copper prices have been trending downwards, although they were occasionally propped up by supply disruptions in Chile and Peru, expectations for the re-opening of the People's Republic of China (hereafter, "China"), and low inventory levels. Prices have continued to fall in the first few months of 2023 as new supplies came online while Chinese demand remains subdued.

Copper production started to pick up in 2022 after several flat years. The Quellaveco mine in Peru started operation in July 2022 and the expansion at Kamoa Kakula in the Democratic Republic of the Congo made a sizeable contribution to production growth. Other existing mines, such as Oyu Tolgoi in Mongolia and Quebrada Blanca in Chile, are moving from the expansion phase to production. The Udokan project in the Russian Federation (hereafter, "Russia") is scheduled to begin operation in 2023, producing 100 kt/year and eventually aiming to supply 400 kt/year to Asian markets, in particular China and India, although sanctions could affect its development. These new supplies, coupled with relatively modest demand growth, are likely to put the overall market balance into surplus in 2023 and 2024.

A closer look beyond 2024, however, reveals a different story. Existing operations are still encountering challenges, as Chile faces declining ore grade and water shortages, and protests from local communities could disrupt Peruvian supplies. Moreover, the lack of high-quality, large-scale

projects in the pipeline indicates that the rate of production growth may decelerate after 2024. This implies that the market could turn into deficit if demand were to increase due to the recovery of the Chinese economy and the acceleration of energy transitions, which would have long-term price implications.

Lithium

In just a decade, the lithium industry has undergone a drastic transformation, with batteries now being the dominant use of lithium. The lithium market is currently experiencing a period of rapid expansion. Following a doubling of demand in 2021 compared with 2017, lithium consumption witnessed an additional 30% growth in 2022. Production levels are also increasing at a significant pace, with an annual growth rate ranging between 25% and 35%. Lithium is attracting substantial attention from mining investors.

The brisk pace of market growth has been accompanied by volatile prices over the past two years. After a relentless rise until early 2022, prices cooled off due to destocking in Chinese markets and growing supplies, although they have recently started to head upwards again. In 2022, there was a deficit of lithium chemical supplies, particularly in battery-grade products. However, this shortfall gradually eased in 2023 due to increased supply from both existing producers and new entrants. Nonetheless, prices for battery-grade materials may remain elevated

due to robust expectations for demand growth, the challenges associated with producing and qualifying as a battery-grade product, and the higher cost profile of non-brine plays.

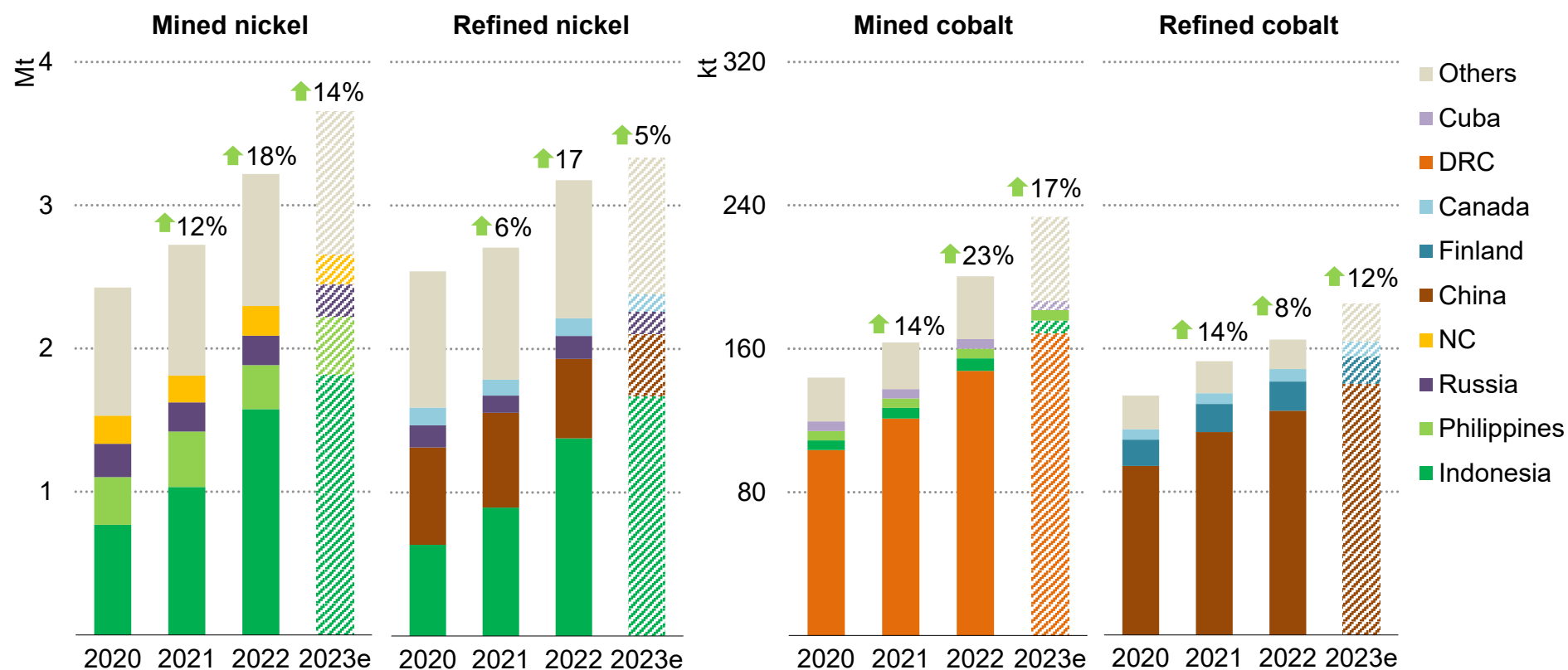
Historically, the majority of lithium mining capacity has been concentrated in Chile's salt flats and Australia's "hard rock" spodumene ore mines, with China dominating the downstream refining process. In recent years, China has progressively ramped up its domestic lithium mining capacity, though it is less competitive due to deposits' challenging geological conditions (lepidolite hard rock ore, high magnesium salt flats). In 2022, there was a notable increase in interest in lepidolite plays, particularly in Jiangxi province, due to their ample resource base. Companies such as CATL, Gotion and BYD have announced [investments](#) in expanding lepidolite mining and conversion facilities. However, significant hurdles remain to support the meaningful growth of lepidolite plays. These include a higher cost profile compared with other lithium sources and the substantial amount of waste and refining slag associated with their development. It is also challenging to produce battery-grade lithium from lepidolite.

Mining projects are also slated to come online in Canada and Argentina in the short run. Additionally, notable developments are occurring in Brazil, where the Grota do Cirilos mine recently commenced production, as well as in several European and African countries. Projects are also underway to diversify downstream processing capacities that transform lithium carbonate into lithium hydroxide, which were traditionally concentrated in China. New investments are being made in conversion capacities closer to mines, as well as in some other consumer countries.

Although the longer-term outlook is promising, new supply projects face some near-term uncertainties. The recent decline in lithium prices could pose challenges to junior miners and early-stage projects. Some projects are facing challenges with slow ramp-ups and construction processes. The impact of low prices on production routes will not be uniform. Non-integrated lithium refiners in China are likely to face difficulties at current price levels, while existing Australian hard rock mining operations and South American salt flats may retain their competitiveness in the market.

Indonesia emerged as the world's largest nickel mining and refining centre; the DRC-China supply chains remain strong for cobalt

Production trends for nickel and cobalt



IEA. CC BY 4.0.

Notes: NC = New Caledonia. DRC = Democratic Republic of the Congo.

Source: IEA analysis based on S&P Global and Benchmark Mineral Intelligence.

Trends for nickel and cobalt

Nickel

Nickel, a vital raw material in the production of stainless steel and batteries, has faced challenges of illiquidity in trading and volatility in prices due to its concentration of supply and geopolitical tensions. Classified into Class 1 and Class 2 based on their respective purities, Class 1 nickel is primarily used for battery cathodes and is sourced from Russia, Canada and Australia, while Class 2 nickel, used for industrial alloys, is mainly supplied by Indonesia, the Philippines and New Caledonia.

After the market squeeze in March 2022, the London Metal Exchange (LME) suspended Asian trading hours to contain volatility, which only restarted a year later. Although the LME has put forth a two-year action plan to boost its markets, which involves establishing daily price limits and creating China-based spot market offerings for nickel sulphate and nickel matte, the speed at which trading liquidity among Asian market participants recovers remains uncertain. Meanwhile, CME Group in Chicago is planning to launch a nickel contract particular to Class 1 nickel.

In 2022, the industry added a record amount of supply, with mined nickel production up by 18% and refined nickel production up by 17%. This surge in supply was primarily driven by Indonesia, which experienced a staggering 50% growth in both mined and refined nickel supplies, putting the market balance into surplus. Adding to its established position as the

world's largest nickel miner, the country overtook China as the largest refined nickel producer, although many of new capacities have been financed by Chinese companies.

Indonesia remains the leading producer of Class 2 nickel. However, its joint venture with Chinese companies in high-pressure acid leach (HPAL) plants is enabling the processing of its laterite resources into Class 1 products. The conversion of nickel pig iron (NPI) into nickel matte, which can be further refined into battery-grade nickel, is also coming into fruition. The ramp-up of nickel processing in Indonesia is expected to continue, with the country having a number of additional HPAL plants in the pipeline. Nonetheless, concerns over waste disposal from HPAL plants remain as the geography and climate of Indonesia pose challenges to environmentally safe options to treat the waste. The NPI-to-nickel-matte route faces challenges associated with higher energy consumption, water protection, risks to biodiversity, erosion and associated emissions.

Several new nickel development projects are currently underway outside of Indonesia, particularly in Australia and Canada. In the Philippines, the second-largest supplier of nickel laterite, only two HPAL plants are currently operating with more being considered, one of which is [a joint venture](#) between a local company and a Chinese company. However, it is unlikely that these projects will pose a significant challenge to Indonesia's dominant position in nickel supplies. One key uncertainty revolves around whether Indonesian nickel will qualify for subsidies

under the US Inflation Reduction Act (IRA) and the regulatory pressures being brought by the European Union on the GHG footprint of batteries. The outcome of this qualification will have implications for the competitiveness of Indonesian nickel in the global market.

Cobalt

After reaching a peak of USD 80 000 per tonne in March 2022, cobalt prices underwent a consistent downward trend and remained around USD 50 000 per tonne throughout the remainder of the year. The muted economic outlook, coupled with China's stringent lockdown measures, had a detrimental effect on consumer electronics demand, impacting the overall demand for cobalt. The low demand was additionally impacted by the cost-cutting strategies of Chinese EV battery producers, opting for cheaper high-nickel chemistries with reduced cobalt content or cobalt-free lithium iron phosphate (LFP) batteries.

Concurrently, the subdued demand for cobalt coincided with an upsurge in supply as numerous mines resumed production in 2021 and 2022. Glencore successfully reopened the Mutanda mine in the Democratic Republic of the Congo, which had been under suspension since 2019, and brought it back into full operation during 2022. In December 2022, Eurasian Resources Group and Gecamines, the national mining company in the Democratic Republic of the Congo, restarted operations at the Boss mine, which had also been suspended since 2019. Exports from the Tenke Fungurume mine, which had been blocked since July 2022, [resumed](#) in April 2023 as China's CMOC and the Democratic

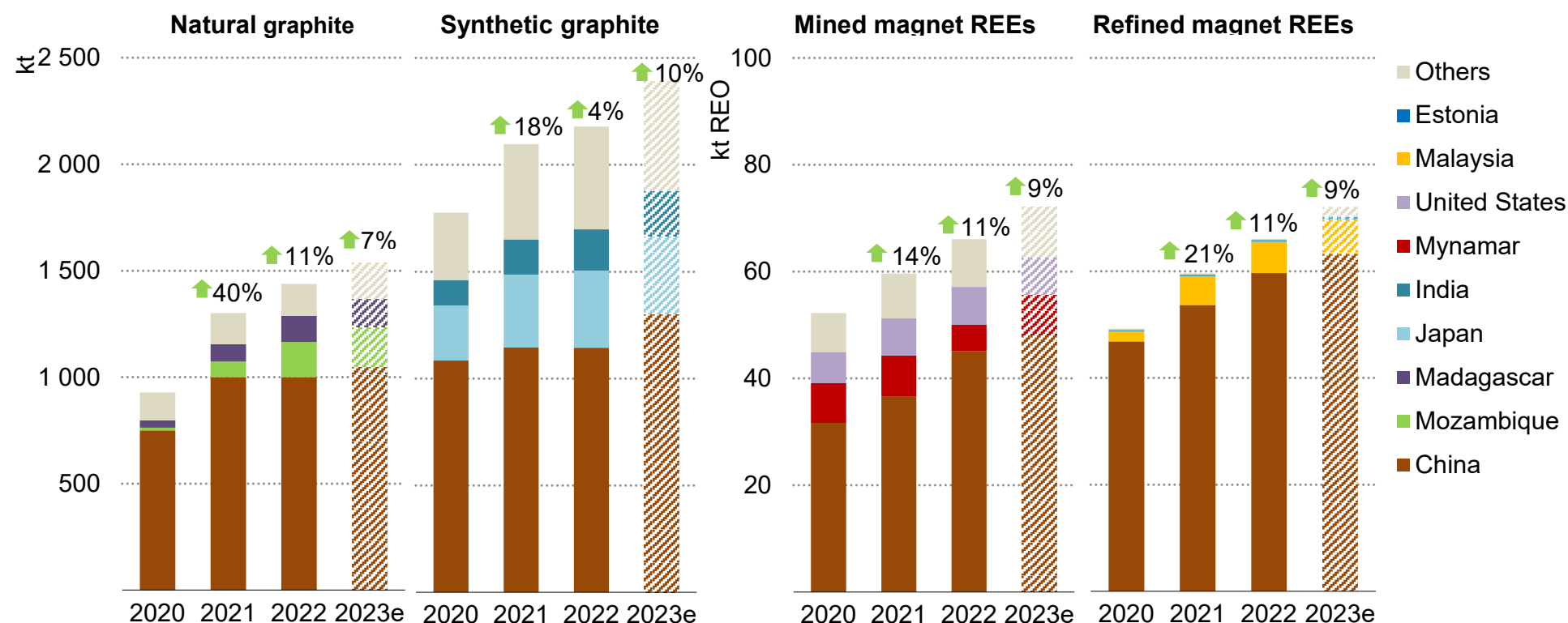
Republic of the Congo's state-owned mining company Gécamines settled a dispute over royalties. Overall, mined cobalt supply experienced a significant surge in 2022, growing by 20%, which resulted in a substantial surplus in the market by year-end.

The Democratic Republic of the Congo maintained its strong position as the leading cobalt producer, accounting for over 70% of global production in 2022. Elsewhere, Indonesia made notable strides, becoming the second-largest supplier of mined cobalt. In 2022, Indonesia tripled its cobalt production with the commencement of new HPAL projects. The United States also marked the country's first cobalt production since 1994 as production began at the Idaho Cobalt Operations in October 2022. However, due to a lack of domestic processing capabilities, these ores are to be exported. With a robust pipeline of projects in the Democratic Republic of the Congo and Indonesia amid the restrained price conditions, the dominance of these two countries in global cobalt supplies is anticipated to persist, while China continues to maintain a stronghold in refined product supplies. China accounted for over 75% of refined cobalt output in 2022.

Looking ahead to the remainder of 2023, cobalt prices are expected to remain suppressed due to oversupply. The Democratic Republic of the Congo is projected to further increase its production. CMOC, the world's second-largest cobalt producer, is scheduled to commence production at the Kisanfu mine in 2023. Indonesia is set to add more volumes as the country produces cobalt as a by-product of its growing nickel industry.

Graphite and rare earth elements are set to gain increasing traction in the critical minerals discussion

Production trends for graphite and rare earth elements



IEA. CC BY 4.0.

Notes: t = tonne; REE = rare earth elements, REO = rare earth oxide. Natural graphite is based on production of natural flake graphite, Magnet REEs include neodymium, praseodymium, dysprosium and terbium.

Source: IEA analysis based on Wood Mackenzie and Adamas Intelligence.

Trends for graphite and rare earth elements

Graphite

Composed of layers of graphene, graphite is a material used in multiple industries, from refractory material to lubricant. But demand is growing fastest for use in batteries. Graphite can be sourced from natural deposits or produced artificially. Some 70% of the natural flake graphite in 2022 is supplied from China, which is also the main producer of synthetic graphite and anode. A process to make spherical graphite that is used for batteries takes place almost entirely in China. Several companies are looking to develop plants outside of China, including [Syrah Resources' Vidalia plant](#) in the United States.

Battery producers have favoured synthetic graphite for its greater reliability, leading to longer battery longevity. Almost 80% of anodes [manufactured](#) in China are made using synthetic graphite. But production requires coke and temperature above 2 500° C, leading to considerable CO₂ emissions. On the other hand, natural graphite is cheaper and less energy-intensive to produce. Thanks to technological development, the reliability of natural graphite quality has been improving over the past few years. For these reasons, the market share of natural graphite is expected to increase in the coming years.

The prices of natural graphite continue to remain subdued due to weak demand and elevated stock levels. However, production capacity for anodes is [exploding](#), with an announced capacity of 13 Mt per year in 2025, compared with 0.8 Mt in 2021, most of which being concentrated

in China. Graphite production is also increasing but at a slower rate, raising concerns about tight supplies in the coming years, particularly for battery-grade products.

Alternatives to graphite in anodes do exist. Silicon can be used to replace some of the graphite to improve the capacity and the energy density of the anode. Silicon-doped graphite already entered the market a few years ago, and now about 30% of anodes [contain](#) silicon. Another option includes lithium metal anodes, which could yield even greater energy density when they become commercially available.

Rare earth elements

Rare earth elements (REEs) are essential for permanent magnets required by EVs and wind turbines. In 2022 and into 2023, China remained the world's largest producer and processor of REEs, accounting for 70% of production and 90% of processing, and Myanmar remained a significant exporter of rare earth ores to China. Against the backdrop of the Covid-19 pandemic, border closures between Myanmar and China remained in place at the beginning of 2022, causing significant supply constraints and uncertainty. The Chinese export price of neodymium-praseodymium oxide rose by 30% in March 2022 from the beginning of the year. While the import restrictions were eased later in April, weak automotive production and the slowing economic recovery dampened REE demand, resulting in price decreases to levels last

observed in July 2021. The prices recovered to some extent in the latter half of 2022, supported by expectations of China's re-opening. In China, three state-owned entities [merged](#) in December 2021, creating the China Rare Earth Group, which accounts for over 60% of the country's heavy REE supply. The reconstruction of the REE industry continued throughout 2022, including the promotion of strategic co-operation between China Rare Earth Group and Guangdong Rising Holdings. The consolidation aims to improve production efficiency and environmental performance of the Chinese REE industry, but could also increase the new entity's pricing power of key REEs such as dysprosium and terbium, with implications for the global REE industry. The Chinese government increased its 2023 quota for REE mining by 20% over 2022 levels,

further raising production (mainly light REEs). In Myanmar, while Chinese Covid-19 restrictions at their border ended by the end of 2022, local residents' protest against environmental pollutions began in December, and, as of April 2023, Chinese mining companies are reportedly preparing [suspension of mining activities in Myanmar](#). Globally, several processing projects are in development, including in the United States (MP Materials) and Canada (SRC), and in 2022, the [United States](#), [Australian](#) and [Canadian](#) governments funded domestic REE mining and processing plants. In 2023, the Japanese government provided additional funding to Lynas to build a heavy REE separation and production facility, aiming to diversify heavy REE supplies away from China.

Trends for other key commodities

Aluminium

Spurred by Russia's invasion of Ukraine (Russia makes up about 5% of global aluminium ingot supply), the prices of aluminium soared in early 2022, reaching a record high level of USD 3 210 per tonne on 7 March. However, the price trajectory shifted course in early summer 2022 due to economic slowdowns in China and other regions. Consequently, prices declined to a range of USD 2 000 to USD 2 500 per tonne during the latter half of 2022 and throughout 2023.

Considerable focus has recently been directed towards Russian exports, potential restrictions on bauxite exports from Indonesia and curtailed supplies in Europe. European smelters have been grappling with soaring energy prices, power shortages, and consequent reductions in their operations. This situation has resulted in the LME inventories reaching their lowest level since 1990.

China remains a critical actor and is poised to shape future market dynamics, in terms both of demand and supply. On the supply side, the hydropower shortage in Yunnan province has prompted smelter curtailments of 1.3 Mtpa in September 2022 and again in February 2023, leading to a swift tightening of the market. If power shortages persist and result in further smelter curtailments, the market could experience noticeable consequences. Thus far, the impact of supply curtailments has been mitigated by weak demand in China. However, the situation could quickly change if Chinese demand were to significantly rebound in

tandem with an economic recovery. It is important to monitor any shifts in developments in China as they could have a substantial influence on the market conditions.

Manganese

Manganese is primarily used as an ingredient in alloy steel. Although batteries currently account for a small percentage of the overall demand for manganese, their share is expected to increase as nickel manganese cobalt (NMC) batteries increasingly incorporate manganese and nickel instead of cobalt. To meet the requirements of batteries, high-purity manganese sulphates are needed, and these are primarily produced by a handful of companies, mostly located in China.

China produces 97% of battery-grade manganese sulphate and there are just a couple of refineries elsewhere, in Japan and in Belgium. Producing high-purity manganese involves a complex process that must be tailored to different ore types. China has accumulated significant experience and expertise in addressing these challenges, making it difficult to diversify the supply chain. Several refining projects are being considered outside China, including the Czech Republic (Euro Manganese), South Africa (Giyani Metals), Canada (Canadian Manganese, Euro Manganese), Australia (Element 25) and the United States (South32). However, with growing trends to adopt manganese-

rich chemistries in batteries, the lack of projects to supply high-purity manganese may well pose a bottleneck for the uptake of EVs.

Platinum group metals

Since autocatalyst is the major user of platinum group metals (PGMs), weak automotive productions affected demand for platinum and palladium through the first half of 2022, pressuring prices. For the supply side, South Africa is the world's largest producer of platinum and palladium accounting for 80% and 45% respectively, followed by Russia, with 10% and 40%, highlighting the impacts of Russia's invasion of Ukraine on supply and price trends. The other major supply-side issue was the power cuts and maintenance challenges in South Africa. In the third quarter of 2022, Mogalakwena, the world's largest open-pit platinum mine, reduced production by 6% from the previous year, and Amandelbult reduced production by 12%, partly because of local protests and power outages. PGM prices are expected to rise in the remainder of 2023 as the global deficit of platinum continues with supply disruption in South Africa and Russia.

Uranium

Growing concerns on energy security and clean energy transitions have underscored the role of nuclear in the decades to come, bringing tight market conditions for uranium in 2022. While there is no open market for uranium, traded spot prices for uranium oxide spiked to nearly USD 60 per pound in March 2022, stabilising around USD 50 per pound afterwards. This level remains significantly higher than prices seen in the

previous five years as spot prices largely remained between USD 20/pound and USD 30/pound. The spread between the spot price and those seen in long-term contracts has also narrowed, with long-term contracts commanding premium of only USD 2/pound to USD 3/pound thus far in 2023, compared with an average premium of over USD 5/pound in 2019 and 2020.

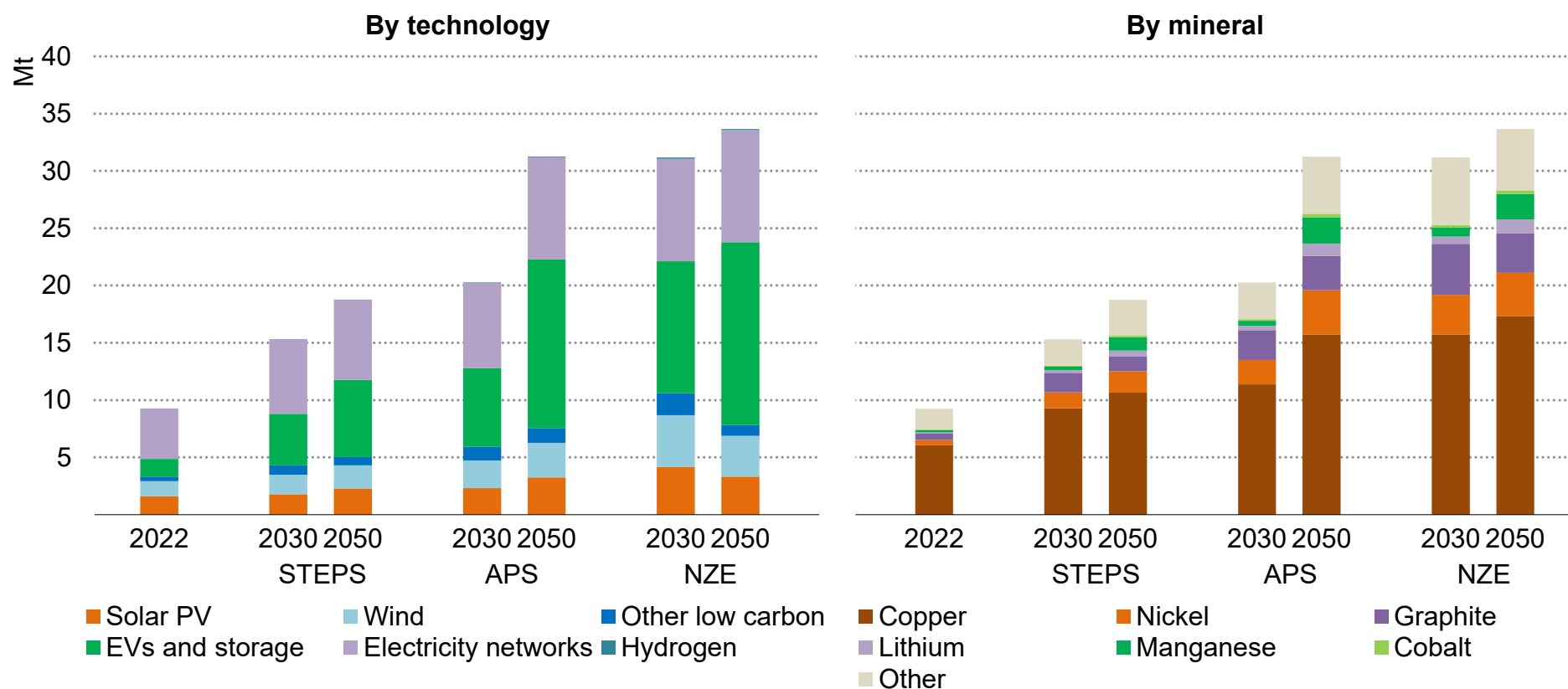
In recent years, Russia has been a significant supplier in the nuclear fuel market. While Russia produces only [around 5% of uranium oxide production](#), it also plays a pivotal role in the market through its conversion and enrichment plants. Kazakhstan is the largest producer of uranium in the world, and as it has no domestic conversion or enrichment facilities, much of its production relies on Russia to reach the world market. These dynamics create major uncertainties for supply in the light of Russia's invasion of Ukraine.

Against this backdrop, a number of projects could potentially expand production, notably sites in Canada, Kazakhstan and the United States that have been idled due to low prices. This includes McArthur River and Key Lake in Canada and multiple sites in Kazakhstan. At the same time, the United States Department of Energy has begun [purchases on the open market to support a strategic uranium reserve](#) from uranium that are produced at a US facility. In the longer term, overall uranium requirements for the global nuclear reactor fleet is [expected to grow](#), but the precise magnitude of this growth is uncertain. At the low end of growth expectations, existing and committed production may be sufficient to meet demand up to 2030 – at the higher end, additional projects would likely be needed.

Implications

Critical minerals demand for clean energy is set to grow by up to three-and-a-half times over the period to 2030 as the world moves through energy transitions

Mineral requirements for clean energy technologies by scenario

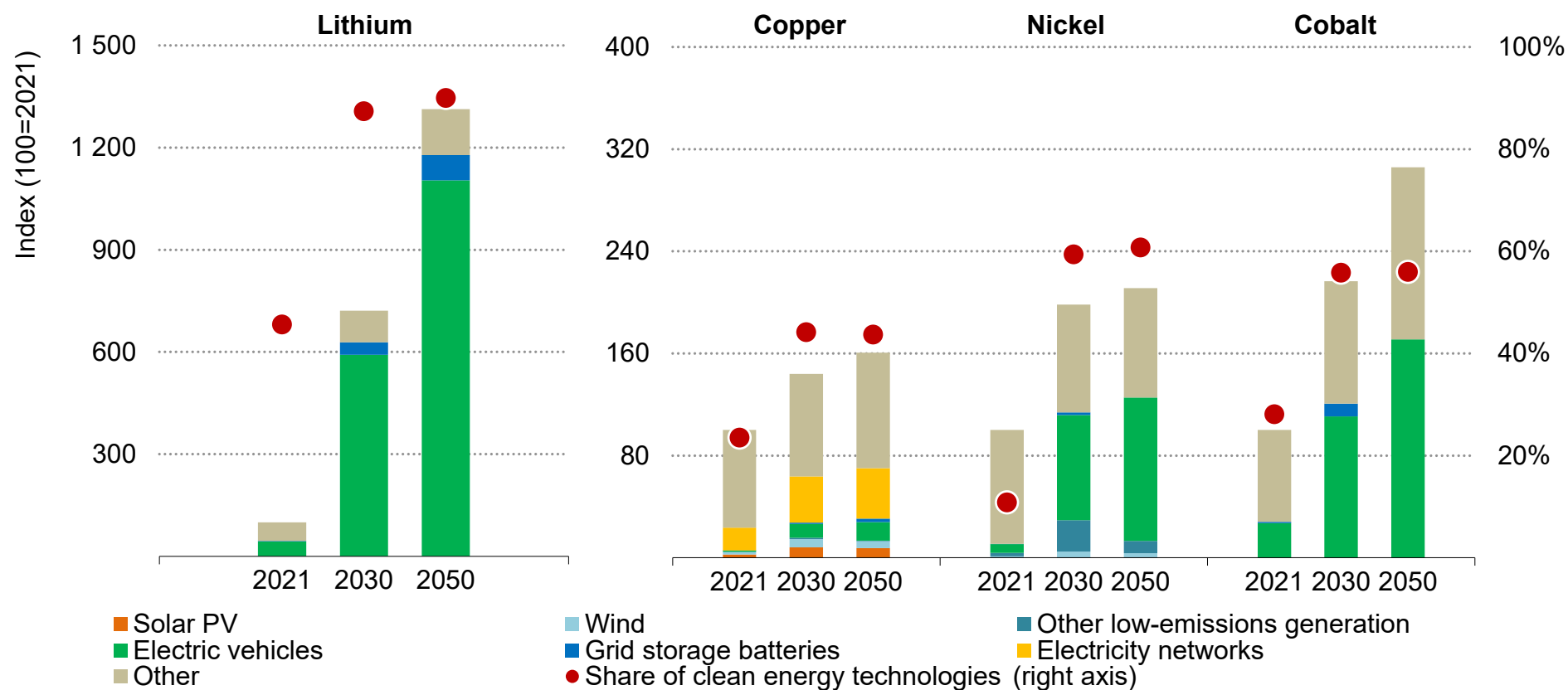


IEA. CC BY 4.0.

Notes: STEPS = Stated Policies Scenarios; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. Includes most of the minerals used in various clean energy technologies, but does not include steel and aluminium.

Clean energy technologies continue to be a major force in driving demand growth for key minerals

Global critical minerals demand by end use in the NZE Scenario



IEA. CC BY 4.0.

Two years on, what do the demand prospects look like?

Since its landmark [special report](#) in 2021, the IEA has been updating its projections for future mineral demand based on the latest policy and technology developments in the [World Energy Outlook 2022](#) and the [Global EV Outlook 2023](#). These updated projections are based on the three IEA energy scenarios:

- **Stated Policies Scenario (STEPS):** this scenario maps out a trajectory that reflects current policy settings, based on a detailed assessment of what policies are actually in place or are under development by governments around the world.
- **Announced Pledges Scenario (APS):** this scenario assumes that all long-term emissions and energy access targets, including net zero commitments, will be met on time and in full, even where policies are not yet in place to deliver them.
- **Net Zero Emissions by 2050 (NZE) Scenario:** this scenario sets out a pathway for the global energy sector to achieve net zero CO₂ emissions by 2050.

Demand for critical minerals for clean energy technologies is set to increase rapidly in all three scenarios. In the APS, demand more than doubles by 2030 and is 3.5 times higher by 2050. In the NZE Scenario, an even faster deployment of clean energy technologies implies an increase in demand for critical minerals by three-and-a-half times in 2030 and 2050, compared with today, reaching over 30 million tonnes.

EVs and battery storage are the main drivers of demand growth, but there are also major contributions from low-emissions power generation and electricity networks.

Two years on, our latest demand projections differ from those in the special report in 2021 for several reasons.

- Projected demand in the STEPS has been revised upwards due to a range of new policy measures that support stronger deployment of clean energy technologies (e.g. the US Inflation Reduction Act [IRA]).
- The APS and the NZE Scenario became the main climate-driven scenarios replacing the Sustainable Development Scenario. The APS considers all climate pledges made by governments and the implications for countries that have not made ambitious long-term pledges, but nonetheless benefit from the accelerated cost reductions for clean energy technologies. The APS is associated with a temperature rise of 1.7° C in 2100 (with a 50% probability), while the NZE Scenario limits global warming to 1.5° C.
- The NZE Scenario reflects the impacts of behavioural changes that tame preferences for larger vehicles (e.g. lower SUV share). This results in the average battery size peaking in this decade and gradually declining thereafter, lowering mineral requirements compared with what would otherwise have been.

- The updated projections reflect the latest developments on battery chemistries, including a higher share of lithium iron phosphate (LFP) and a faster switch to high-nickel chemistries. This had a notable (downward) impact on cobalt demand.
- Mineral demand for electricity networks has been updated based on a granular assessment of grid line deployment by type (overhead, underground) and voltage levels. The updated projections also consider a higher share of aluminium in low-to-medium voltage segments.
- Material intensity assumptions have been updated based on the latest literature review and industry consultations. For batteries, the updated projections incorporate the latest intensity assumptions in the [GREET-2022](#), which are slightly lower than in the previous assumptions.

Although each factor had a different impact on projected mineral requirements, overall, projected demand in the STEPS is higher than

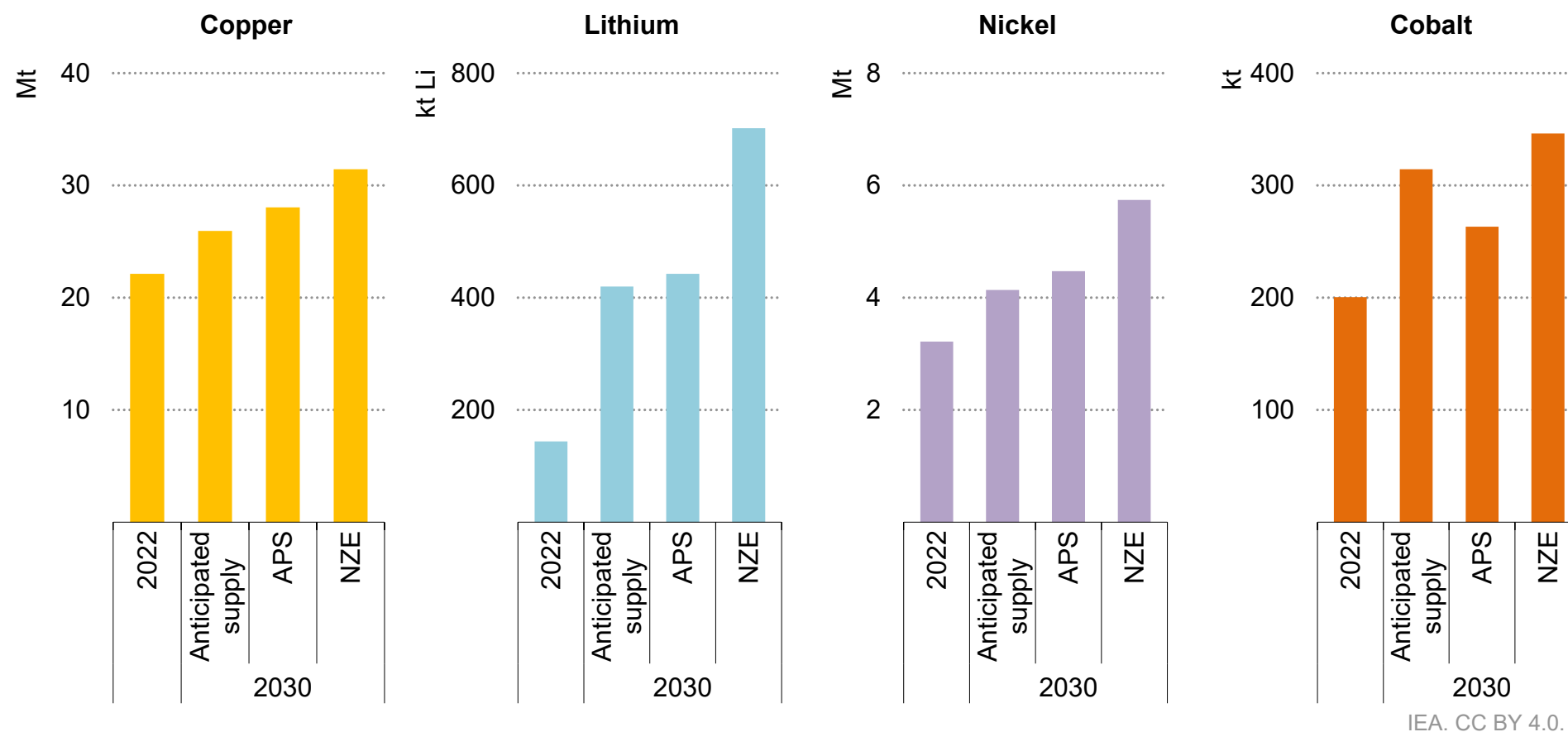
that in the 2021 report, whereas demand in the NZE Scenario is lower, most notably due to the moderate battery size growth.

Nonetheless, even with the lowered demand in the NZE Scenario, projected mineral demand in climate-driven scenarios is multiple times higher than today, putting clean energy technologies at the forefront of driving total mineral demand growth. From copper to lithium and to cobalt, clean energy technologies emerge as the largest consuming segment of demand, pushing their share in total demand considerably higher than today.

It is important to note that demand projections are inherently subject to large variations, not only affected by energy scenarios but also by technology choices and behavioural factors. The IEA developed more than ten alternative cases to quantify the impacts of different consumer choices and technology developments on future mineral requirements. The results of these cases will be available through the IEA Critical Minerals Data Explorer, an accompanying online data tool (see Annex).

Supply is catching up with countries' ambitions with a host of newly announced projects, but well balanced markets are far from assured

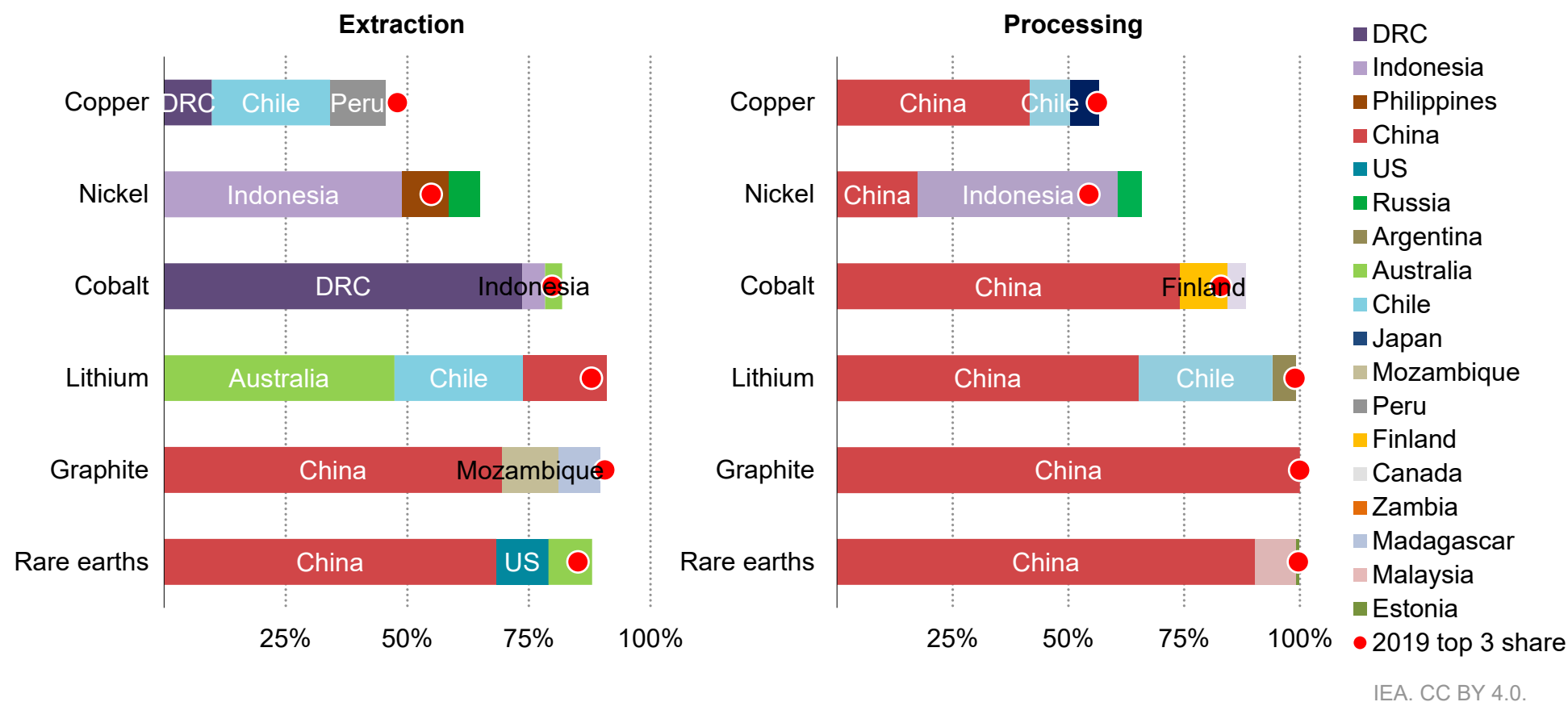
Anticipated primary production and primary supply requirements of selected minerals in the APS and NZE Scenario



Note: Primary supply requirements are calculated as “total demand net of secondary supply”.
Sources: IEA analysis based on S&P Global, BNEF and Benchmark Mineral Intelligence.

There has been limited progress in terms of diversification over the past three years; concentration of supply has even intensified in some cases

Share of top three producing countries in total production for selected resources and minerals, 2022

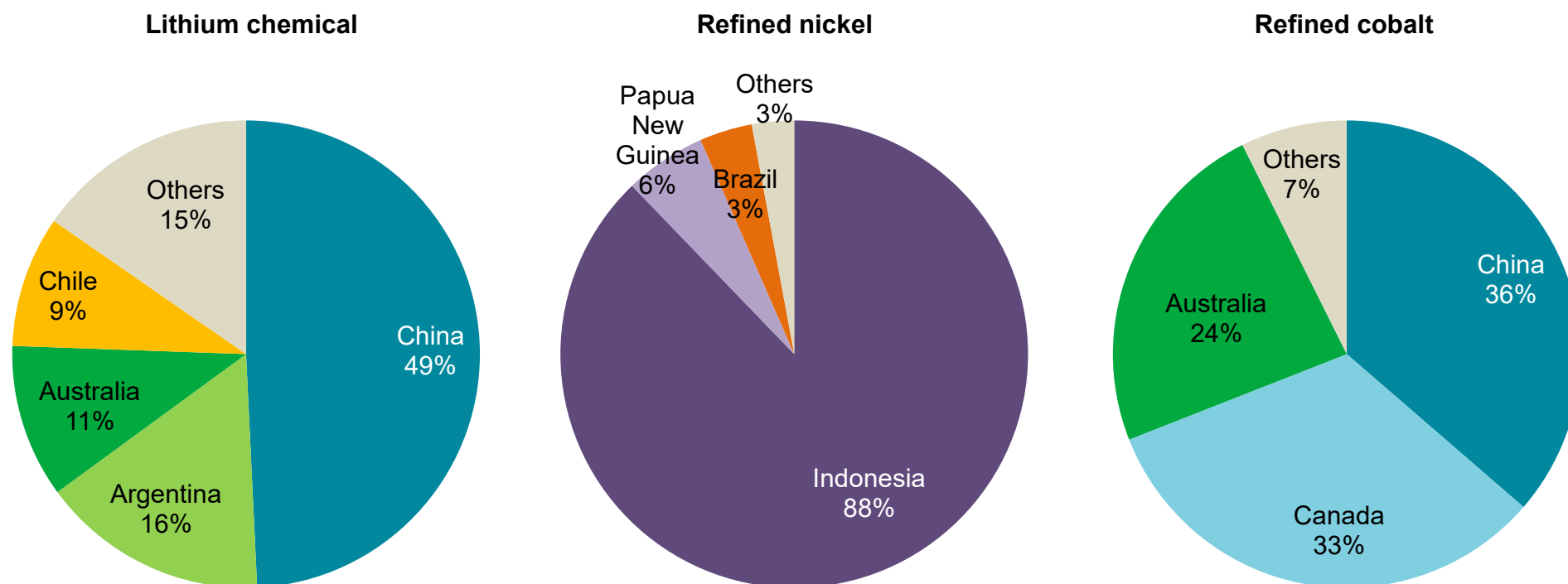


Notes: DRC = Democratic Republic of the Congo. Graphite extraction is for natural flake graphite. Graphite processing is for spherical graphite for battery grade.

Sources: IEA analysis based on S&P Global, USGS (2023), [Mineral Commodity Summaries](#) and Wood Mackenzie.

Analysis of project pipelines indicates that, in most cases, the geographical concentration of refining operations is likely to remain high in the near term

Geographical distribution of planned refining projects for key minerals, 2023-2030

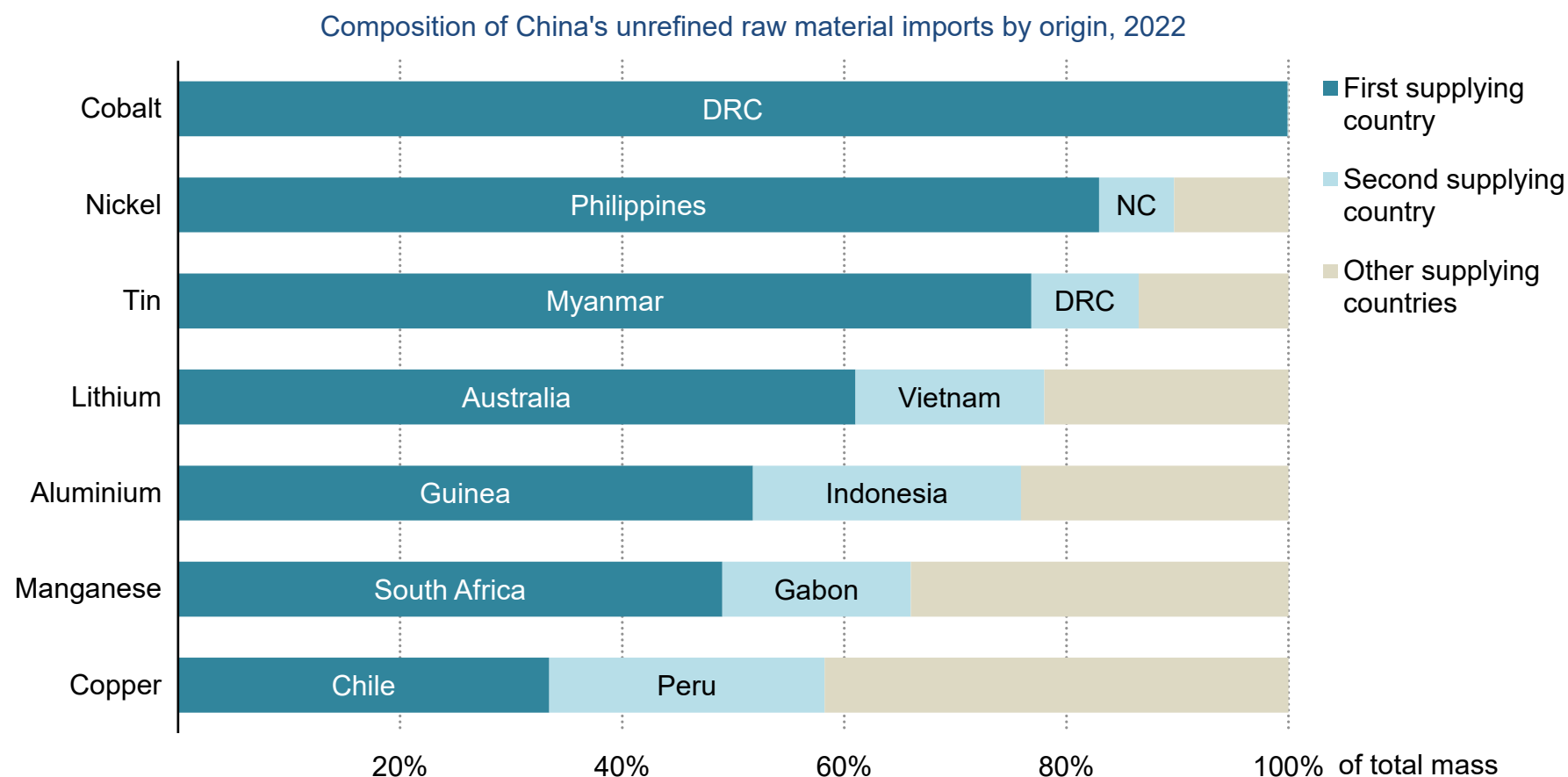


IEA. CC BY 4.0.

Notes: Included firm and probable projects. The shares are based on projected 2030 supply.

Sources: IEA analysis based on Wood Mackenzie and Benchmark Mineral Intelligence.

China's push to diversify raw material supplies hint at greater competition for mining assets around the world



IEA. CC BY 4.0.

Notes: DRC = Democratic Republic of the Congo; NC = New Caledonia. Trade data for cobalt, nickel, tin, lithium (spodumene), aluminium (bauxite) and copper hard rock ores and concentrates.

Sources: IEA analysis based on China Custom data, BMO capital markets.

Box 3. What makes it tough to diversify refining and processing operations?

Despite the increasing interest in diversifying refining and processing operations, significant progress in this area has yet to be made. The industry has historically favoured concentrated global “hubs” that specialise in the metallurgical and chemical transformations necessary for high-tech applications. Examples include the production of cathode active materials for batteries, the conversion of lithium into hydroxide form, and the treatment and separation of rare earth ore into oxides. As a result, supply chains for refining and processing have become more concentrated than those for mining.

Developing new refining and processing projects in diversified areas presents significant challenges for investors, which include:

- **Limited pricing power:** Positioned between the raw materials and the downstream value chain, the refining and processing industry has frequently faced margin pressures due to the market power of the extractive industry and dominant downstream equipment manufacturers. While the intermediate supply chain had to navigate the price volatility between raw material prices and downstream component prices, price hedging often proved difficult in relatively small and illiquid markets.
- **Insufficient value placed on diversification by consumers:** Downstream actors have often prioritised short-term profits over the importance of diversified supply chains, as the risks associated with concentration are difficult to assess and are sometimes viewed as speculative. Additionally, many consumers have established off-take contracts with established players, which further intensifies competition for new entrants.
- **Exposure to distortive market behaviours:** When incumbent players or regions possess significant market power in shaping prices, new entrants must consider the potential for distorting market behaviours. Furthermore, substantial industrial overcapacities and non-transparent stockpiles within dominant hubs is often observed, which diminishes the attractiveness of project investments in new facilities in other countries.
- **Limited access to technology, skills and supply chains:** Incumbent players possess a substantial advantage through their access to a skilled workforce, well-established component supply chains and accumulated technological expertise. This often translates into higher capital costs, creating barriers to entry for new players, who may struggle to compete on the same resources and capabilities.

Despite the notable challenges, the refining industry stands out for its relatively shorter lead times and its ability to generate substantial employment and added value compared with the extractive sector. Recognising the concerns surrounding the high geographical concentration of refining and processing operations, governments are enacting various policy measures to address this issue. These efforts include providing direct funding through grants and preferential loans, and supporting R&D as well as pilot plant developments. For instance, Japan has a track record of proactively supporting Australia's rare earth element company, Lynas.

The Inflation Reduction Act tax credits are another new policy tools as they provide incentives for downstream actors to favour suppliers in friendly regions, indirectly de-risking investments in refining projects in diversified regions. Strengthening environmental, social and governance requirements would also contribute to creating a more level playing field. Given the energy-intensive nature of refining operations, ensuring affordable and clean energy supplies can also help enhance the competitiveness of the plants. While trade distortions should be minimised, further policy measures are necessary to support geographically diversified supply sources and help businesses and investors recognise the value of diversity.

Three layers of supply-side challenges

When it comes to mineral supplies, there are three layers of challenges that need to be addressed: i) whether future supplies can keep up with the rapid pace of demand growth in climate-driven scenarios to avoid a potential mismatch between demand and supply; ii) whether those supplies can come from diversified sources; and iii) whether those volumes can be supplied from clean and responsible sources.

On the first question, there has been some progress in recent years with notable increases in investment and exploration spending, leading to increased supplies in the coming years. This has reduced the potential mismatch between demand and anticipated supply in 2030, although meeting the requirements in the NZE Scenario still requires further projects to come through. However, while the absolute supply situation has improved compared with several years ago, medium-term pressures remain due to several practical challenges.

- While long lead times to develop new projects are well-known challenges, project execution delays and cost overruns have been prevalent in past experiences, which adds to the challenges of delivering volumes on time.
- There is an important distinction between technology-grade products and battery-grade products, which generally require higher-quality, high-purity outputs and involve a lengthy process to be qualified by end users. Aggregate supply and demand balances do not necessarily reflect the supply dynamics for battery-grade products.

- New plays generally involve higher production costs. From laterite-based nickel to lepidolite-based lithium and to sulphidic-based copper, there is a long list of potential plays that sit on the righter side of cost curves, which would require elevated marginal costs to bring these volumes on stream.
- Thin inventory levels limit the industry's ability to cushion short-term supply disruptions.
- There is the possibility that today's dip in prices will diminish the investment appetite, which would have strong medium-term implications.
- There are uncertainties too on the demand side, but if the world is to achieve its climate goals then there needs to be robust and continuous growth in demand after 2030.

The significance of secure mineral supplies becomes more prominent when we look at the way that we are building up clean energy supply chains. In the case of EV batteries and solar panels, for example, there are increasing announcements to construct new battery gigafactories or solar panel plants, the total of which approaches the necessary scale in the NZE Scenario. However, there is no matching progress on the raw material front. When one component of the value chain progresses quickly while others lag behind, the overall pace of transition will be geared towards the slow-moving one.

Despite some progress on the first supply-side challenge, there is less promise on the second challenge – diversification – and the third challenge – clean and responsibly-produced supplies. Compared with three years ago, the share of the top three producers in 2022 either remains unchanged or has increased further, especially for nickel and cobalt.

Our analysis of project pipelines reveals a somewhat improved outlook for mining, but not for refining operations where today's geographical concentration is greater. Planned projects are mostly developed in incumbent regions, with China holding half of planned lithium chemical facilities and Indonesia representing nearly 90% of planned refined nickel plants. Many resource holding nations are seeking positions further up the value chain while many consuming countries want to diversify their source of refined metal supplies. However, the world has not yet successfully connected the dots to build diversified midstream supply chains. This highlights numerous challenges in diversifying refining and processing operations, which requires further policy support and push (see Box 3).

China's strong position in the refining and processing value chain also implies potentially greater competition for raw material assets in diversified regions. 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 almost entirely on the Democratic Republic of the Congo for mined cobalt to run its refining facilities, and the Philippines and Myanmar account for 75-85% of the country's unrefined nickel and tin ore supplies.

Therefore, as other economies step up efforts to diversify their critical mineral supply chains, China is also seeking ways to diversify its raw material supply portfolio. The country has been actively investing in many mining assets in Africa and Latin America, and its investment in overseas mining assets is likely to grow in the coming years. Between 2018 and the first half of 2021, Chinese companies [invested USD 4.3 billion](#) to acquire lithium assets, twice the amount invested by companies from the United States, Australia and Canada combined during the same period. China is also investing in processing, refining and downstream facilities in other regions, often with an aim to secure strategic access to raw materials. The country's investments in Indonesia's nickel processing plants are well known and BYD recently announced a plan to build a [USD 290 million lithium cathode plant](#) in Northern Chile.

Apart from progress on diversification, a significant proportion of the current mineral supply comes from sources with lower environmental, social and governance scores, highlighting that the industry is far from being able to secure clean and responsible volumes.

To tackle this complex set of challenges, it is crucial to remain vigilant in promoting secure, sustainable, and responsible supplies of critical minerals that play a central role in global clean energy transitions. In this regard, the IEA will host [the first ever international summit on critical minerals](#) on 28 September 2023, bringing together ministers from mineral-producing and -consuming economies as well as industry, investors and civil society to address a range of questions around supply and sustainability.

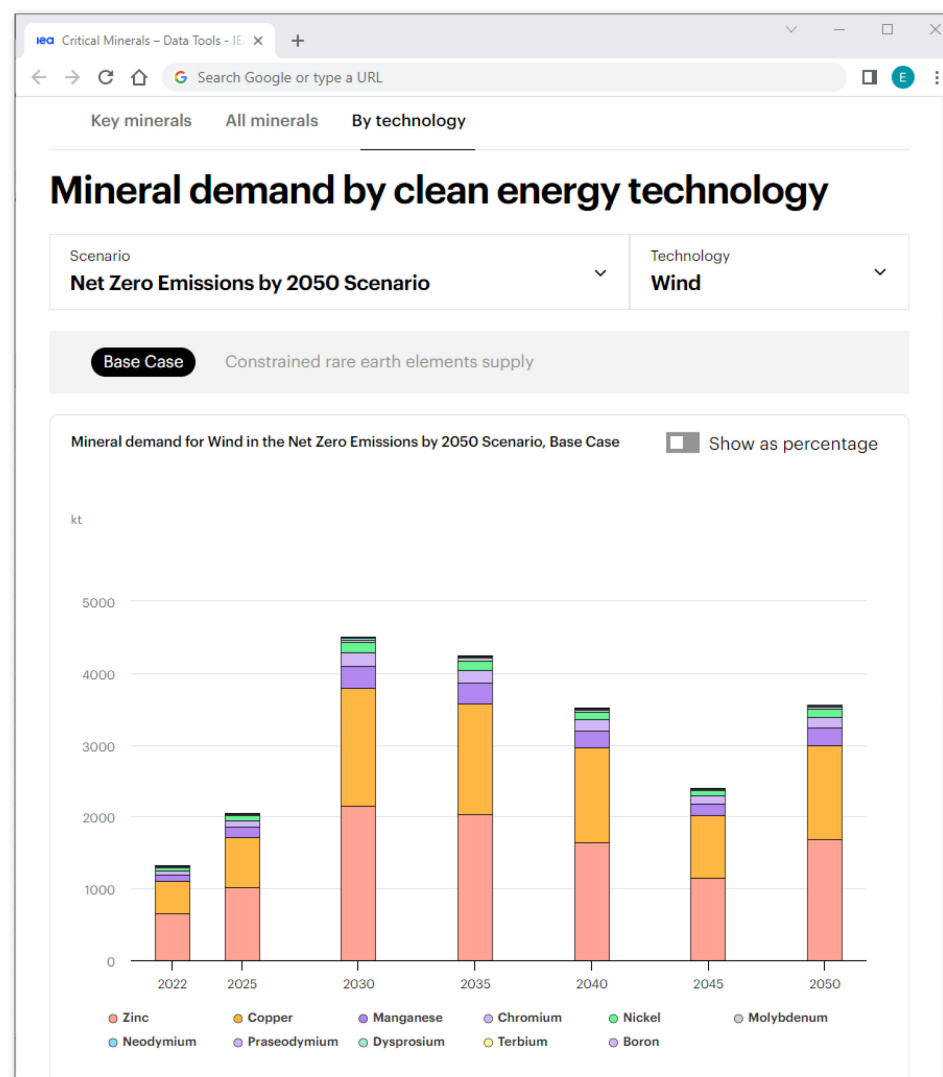
Annex

IEA Critical Minerals Data Explorer

The IEA has integrated critical minerals into its long-term energy modelling framework. Along with the Critical Minerals Market Review 2023, we are launching [the IEA Critical Minerals Data Explorer](#), an interactive online tool that allows users to easily access the IEA's projection data.

In its first release, the tool provides users with access to the IEA's demand projection results under various energy scenarios and technology evolution trends (through ten-plus alternative technology cases). Users can look up total demand for key minerals (copper, lithium, nickel, cobalt and neodymium) and projected mineral demand in the clean energy sector by technology and commodity, scenario and technology cases.

The numbers will be regularly updated to align with the latest energy projections, when the [World Energy Outlook 2023](#) is released. Long-term supply projection data will also be added to the data explorer at a later stage.



Geographical concentration of production

Share of top one and three producing countries in total production for selected resources and minerals

Mined output					Refined output			
	Top 1 share		Top 3 share		Top 1 share		Top 3 share	
	2019	2022	2019	2022	2019	2022	2019	2022
Copper	28%	24%	48%	45%	40%	42%	56%	57%
Lithium	55%	47%	88%	91%	63%	65%	99%	99%
Nickel	34%	49%	55%	65%	32%	43%	54%	66%
Cobalt	73%	74%	80%	82%	68%	76%	83%	90%
Graphite	71%	70%	91%	90%	100%	100%	100%	100%
Rare earth elements	63%	68%	85%	88%	88%	90%	100%	100%

Note: Graphite extraction is for natural flake graphite. Graphite processing is for spherical graphite for battery grade. The figures for rare earth elements are for magnet rare earth elements such as neodymium, praseodymium, dysprosium and terbium.

Sources: IEA analysis based on S&P Global, Benchmark Mineral Intelligence, Adamas Intelligence, USGS (2023), [Mineral Commodity Summaries](#) and Wood Mackenzie.

Acknowledgements

This report was prepared by the Energy Supply and Investment Outlook (ESIO) Division of the Directorate of Sustainability, Technology and Outlooks (STO), 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: Simon Bennett (venture capital investment), Hippolyte Boutin (mining), Eric Buisson (modelling, policy, demand and supply trends), Amrita Dasgupta (clean energy technology and battery trends), Tsuyoshi Deguchi (investment, mergers and acquisitions), Alexandre Gouy (modelling, recycling), Alexandra Hegarty (rare earth elements), Yun Young Kim (manufacturer strategies, cobalt), K.C. Michaels (environmental and social issues), Toru Muta (supply, individual commodity review), Tomás de Oliveira Bredariol (environmental and social issues), Ryszard Pospiech (modelling), Joyce Raboca (environmental and social issues, nickel) and Natalie StClair (environmental and social issues). Eleni Tsoukala provided essential support.

The report benefited greatly from contributions from other experts within the IEA: Mary Warlick, Keisuke Sadamori, Laura Cozzi, Lucila Arboleya Sarazola, Simone Beretta, Eléonore Carré, Jason Elliott, Milosz Karpinski, Teo Lombardo, Dionysia Lyngopoulou, Christophe McGlade and Erica Robin.

Thanks also to Jad Mouawad, Curtis Brainard, Astrid Dumond, Oliver Joy, Jethro Mullen, Julie Puech and Therese Walsh of the Communications and Digital Office. Erin Crum edited the manuscript and Charner Ramsey designed the cover. Jon Custer and Ivo Letra provided support for the data tool.

The IEA Clean Energy Transitions Programme (CETP), particularly through the financial contributions of Ministry of Foreign Affairs in Japan supported this analysis. Thanks also go to the IEA Working Party on Critical Minerals.

Many experts from outside of the IEA provided input and reviewed preliminary drafts of the report. Their comments and suggestions were of great value. They include:

Nobuaki Arima	Ministry of Economy, Trade and Industry, Japan
Morgan D. Bazilian	Colorado School of Mines
Peter Buchholz	Federal Institute for Geosciences and Natural Resources
Shobhan Dhir	University of Oxford
Francesca Gostinelli	ENEL
Scott Greenip	Department of State, United States
Colin Hamilton	BMO Capital Markets
Takeshi Harada	Japan Organization for Metals and Energy Security

Sara Hastings-Simon University of Calgary
Daniel Hill Natural Resources Canada
Benjamin Katz Organisation for Economic Co-operation
 and Development
Nobuyuki Kikuchi Ministry of Foreign Affairs, Japan
John Lindberg International Council on Mining and Metals
Louis Maréchal Organisation for Economic Co-operation
 and Development

Dennis O. Mesina
Mark Richards
Tristan Stanley
Martin Stuermer
Lyle Trytten
Joel Watson

Department of Energy, United States
Rio Tinto
BHP
International Monetary Fund
Independant consultant
Foreign, Commonwealth and
Development Office, United Kingdom

Abbreviations and acronyms

APS	Announced Pledges Scenario
AUD	Australian dollar
CAD	Canadian dollar
CME	Chicago Mercantile Exchange
CO₂	carbon dioxide
CO₂-eq	carbon dioxide equivalent
CRM Act	Critical Raw Materials Act
DRC	Democratic Republic of the Congo
ESG	environmental, social and governance
EV	electric vehicle
G7	Group of Seven intergovernmental forum
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies model
HPAL	high pressure acid leaching
IEA	International Energy Agency
IRA	Inflation Reduction Act
IRMA	Initiative for Responsible Mining Assurance
LCE	lithium carbonate equivalent
LFP	lithium iron phosphate
LME	London Metal Exchange
M&A	mergers and acquisitions
NCA	nickel cobalt aluminium
NMC	nickel manganese cobalt
NPI	nickel pig iron
NZE	Net Zero Emissions By 2050 Scenario

OECD	Organisation For Economic Co-operation and Development
OEM	original equipment manufacturer
PGMs	platinum group metals
PV	photovoltaic
R&D	research and development
REE	rare earth elements
SHFE	Shanghai Futures Exchange
STEPS	Stated Policies Scenario
SUV	sport utility vehicle
TSM	Towards Sustainable Mining
VC	venture capital

Units of measure

Gt	gigatonne
GW	gigawatt
GWh	gigawatt-hour
kg	kilogramme
kt	kilotonne
kWh	kilowatt-hour
m³	cubic metre
mcm	million cubic metres
Mt	million tonnes
Mtpa	million tonnes per annum
MW	megawatt
TWh	terawatt-hours

International Energy Agency (IEA)

This work reflects the views of the IEA Secretariat but does not necessarily reflect those of the IEA's individual Member countries or of any particular funder or collaborator. The work does not constitute professional advice on any specific issue or situation. The IEA makes no representation or warranty, express or implied, in respect of the work's contents (including its completeness or accuracy) and shall not be responsible for any use of, or reliance on, the work.



Subject to the IEA's [Notice for CC-licensed Content](#), this work is licenced under a [Creative Commons Attribution 4.0 International Licence](#).

This document and any map included herein are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Unless otherwise indicated, all material presented in figures and tables is derived from IEA data and analysis.

IEA Publications

International Energy Agency

Website: www.iea.org

Contact information: www.iea.org/contact

Typeset in France by IEA - July 2023

Cover design: IEA

Photo credits: © Shutterstock

