IRENA
International Renewable Energy Agency

CRITICAL MATERIALS

BATTERIES FOR ELECTRIC VEHICLES

ISBN 978-92-9260-626-8

Citation: IRENA (2024), *Critical materials: Batteries for electric vehicles*, International Renewable Energy Agency, Abu Dhabi.

About IRENA

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

Acknowledgements

This report was authored by Isaac Elizondo Garcia, Carlos Ruiz and Luis Janeiro (IRENA) and Martina Lyons (ex-IRENA), under the direction of Francisco Boshell and Roland Roesch (Director, IRENA Innovation and Technology Centre).

Valuable input was provided by IRENA colleagues Deepti Siddhanti, Dora Lopez, Jinlei Feng and Zhaoyu Lewis Wu and Yong Chen.

This report benefitted from the input and comments of experts, Bryan Bille (Benchmark Minerals Intelligence), Claudia Brunori (Italian National Agency for New Technologies, Energy and Sustainable Economic Development), Dana Cartwright (International Council on Mining and Metals), Daniel Weaver (Department for Energy Security and Net Zero, UK), Djibo Seydou (Ministry of Mines, Niger), Dolf Gielen (World Bank), Katherine Shapiro (Ministry of Energy and Natural Resources, Canada), Marcos Ierides (Bax & Company), Maros Halama (InoBat), Shorai Kavu (Ministry of Energy and Power Development, Zimbabwe), Silvia Bobba (Joint Research Centre, European Commission) and Yiheyis Eshetu (Ministry of Water and Energy, Ethiopia). The report was copy-edited by Fayre Makeig and technical review provided by Paul Komor. Editorial support was provided by Francis Field and Stephanie Clarke. Graphic design was provided by Nacho Sanz.

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ABBREVIATIONS

BEV	battery electric vehicle
ESG	environmental, social and governance
EV	electric vehicle
GWh	gigawatt hour
IRENA	International Renewable Energy Agency
kg	kilogram
kWh	kilowatt hour
LCE	lithium carbonate equivalent
LFP	lithium iron phosphate
LMFP	lithium manganese iron phosphate
LMO	lithium manganese oxide
Mt	million tonnes
NCA	nickel cobalt aluminium oxide
NMC	nickel manganese cobalt oxide
NMCA	nickel manganese cobalt aluminium oxide
PHEV	plug-in hybrid electric vehicle
PPA	purified phosphoric acid
R&D	research and development
SUV	sports utility vehicle
Wh	watt hour

EXECUTIVE SUMMARY

Advancing the energy transition will require electric vehicles (EVs) to dominate passenger vehicle sales by 2030. In 2023, the global stock of passenger EVs stood at about 44 million. Achieving the International Renewable Energy Agency's (IRENA's) 1.5°C Scenario requires significant growth of the global stock, to 359 million, by 2030. This electrification imperative extends to all road transport sectors, including those previously deemed unsuitable for electrification, such as long-haul road freight.

While the outlook for EV battery production capacity is positive, ensuring an adequate, reliable and affordable supply of the necessary raw materials is essential. In line with IRENA's 1.5°C Scenario, the electrification of road transport would require EV batteries' annual production to grow five-fold between 2023 and 2030. Even though the current planned battery production capacity for 2030 (7 300 gigawatt hours [GWh]/year) exceeds the anticipated demand for EV batteries (4 300 GWh/year), concerted efforts are still needed to secure the necessary raw materials for these batteries.

Increasing demand for EVs would drive up demand for the materials used in EV batteries, such as graphite, lithium, cobalt, copper, phosphorous, manganese and nickel. Under IRENA's 1.5°C Scenario, the demand for lithium from EV batteries could roughly quadruple from 2023 to 2030. Similarly, the demand for cobalt, graphite and nickel could more than triple. However, innovations enabling the substitution of these materials are already reducing demand; cobalt and nickel were no longer used in nearly half of the passenger EVs sold in 2023.

While resource availability is not a constraint for the long-term decarbonisation of road transport, efforts are needed to quickly and effectively scale up production to meet growing demand in the short to medium term. As highlighted in previous IRENA publications, long-term availability is a matter of expanding production volume and ensuring diversity of supply (Gielen, 2021; IRENA, 2023a). For instance, the annual demand for lithium is estimated to be 2.5-3.1 million tonnes per year (Mt/year) by 2030, with reserves and resources standing at 150 Mt and 560 Mt, respectively, indicating ample supply (USGS, 2024).

Effectively navigating uncertainties in the short to medium term requires regular monitoring and assessment of market dynamics and technological advancements as well as modelling various scenarios. On the demand side, uncertainties primarily result from policies supporting EV deployment and their impact on the projected volume of EV sales; disruptive innovation; and the evolving market share of different anode and cathode chemistries, each characterised by distinct material compositions. On the supply side, uncertainties stem from factors such as fluctuating market prices, regulatory changes and potential disruptions in the value chain due to factors such as natural disasters, geopolitical tensions or trade disputes.

IRENA has developed a supply-demand analysis to understand and explore potential bottlenecks by 2030, assuming a level of EV deployment aligned with the 1.5°C Scenario. Within this context, three battery chemistry scenarios are examined. The first scenario, considered a Technology Stagnation scenario, assumes limited innovation and a continued high share of nickel-rich chemistries. The second scenario, considered a continuation of Current Trends, explores an increasing dominance of lithium iron phosphate (LFP) and lithium manganese iron phosphate (LMFP) batteries.[1] The third scenario, regarded as an Increased Innovation scenario, assumes the prominence of LFP and LMFP alongside a significant increase in emerging sodium-ion technology. To gauge the likelihood of a supply-demand gap under each scenario, a range of supply projections from other organisations is considered.

EV batteries are not driving the demand for all critical materials in EVs. Other industries and applications influencing these materials' availability and pricing should not be overlooked. The demand for EV batteries is a major driver of demand for lithium, and – to a lesser extent - cobalt, graphite and nickel. However, copper, with an approximately 4% demand share from EV batteries by 2030, is primarily driven by construction and power-related infrastructure. Similarly, the demand shares for phosphorus and manganese from EV batteries are estimated to be about 3% and only about 2%, respectively, by 2030.

With sustainable expansion of material supply chains, complemented by continued innovation in battery chemistries, countries can meet the growing demand for EV battery materials. This is possible even under a very fast adoption of EVs, in line with a 1.5°C decarbonisation pathway. A critical factor will be the scale-up of material supply in line with currently available forecasts. Beyond that, faster adoption of innovative batteries with lower critical material requirements (*e.g.* LFP, LMFP and sodium-ion) could further mitigate potential shortages of some materials, even if mining does not scale up as rapidly as expected. A broad range of outcomes is possible depending on the evolution of material supply capacity and the effects of technology innovation. For instance, potential lithium surpluses are estimated at 0.60 Mt/year, or about 25% of the estimated demand in 2030, while shortages could reach up to 1.3 Mt/year, representing about 40% of the estimated demand in 2030 (Figure 1).

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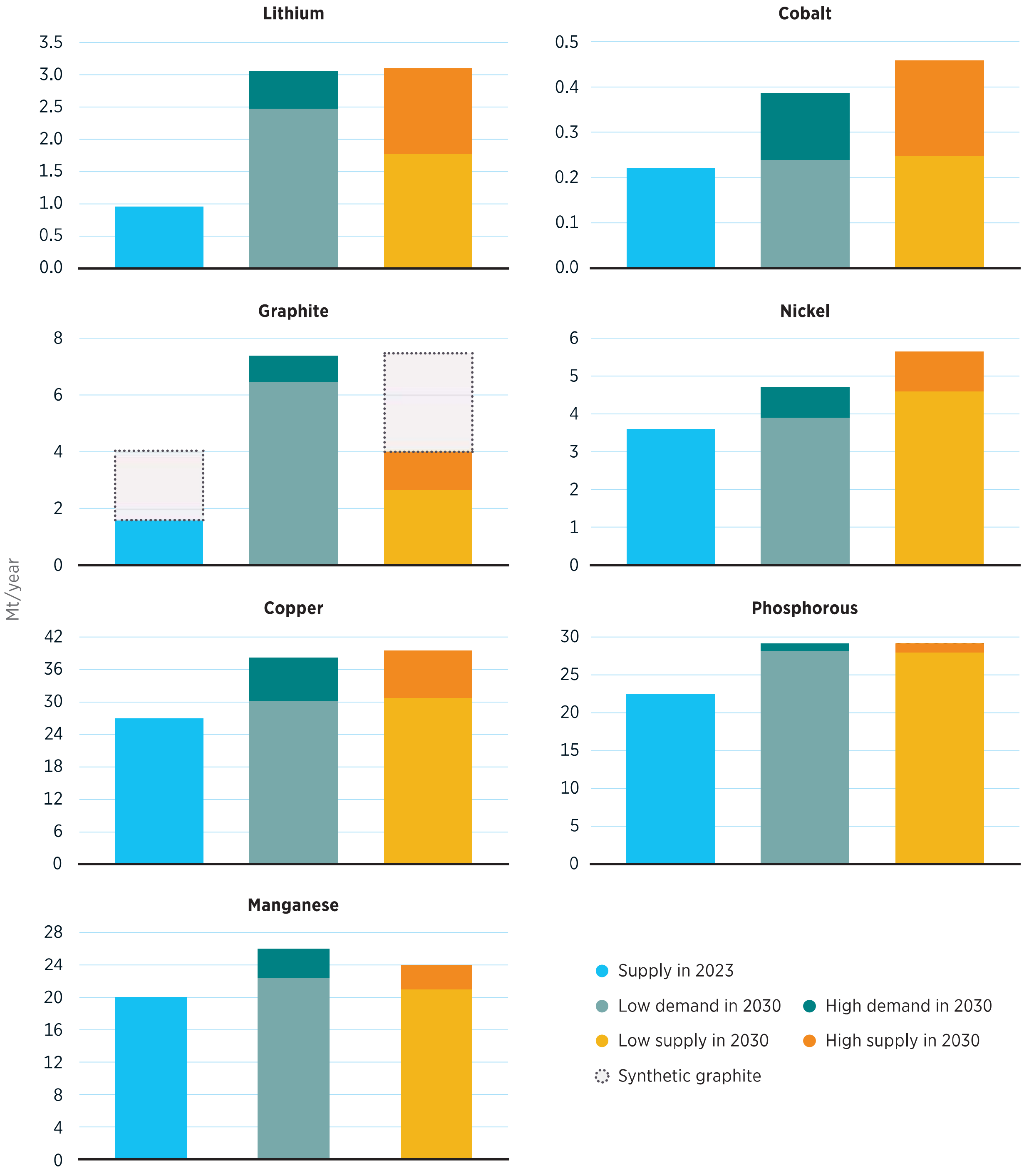
[1] LFP refers to lithium iron phosphate batteries, and LMFP refers to lithium manganese iron phosphate batteries.

FIGURE 1 Critical material supply and demand in 2023 and 2030



Sources: Lithium – supply in 2023 based on USGS (2024); supply in 2030 based on Albemarle (2023), BNEF (2024a), ETC (2023), Fitch Solutions (2022), Jimenez and Saez (2022) and S&P Global (2023). Cobalt – supply in 2023 based on USGS (2024); supply and demand in 2030 based on BNEF (2024a), Cobalt Blue Holdings (2022), Darbar (2022), ETC (2023), Fu (2020), Patterson and Rankumar (2023) and S&P Global (2023). Graphite – supply in 2023 based on USGS (2024); supply in 2030 based on Black Rock Mining (2023), ETC (2023) and WSJ (2023). Nickel – supply in 2023 based on USGS (2024); supply in 2030 based on BNEF (2024b), ETC (2023) and S&P Global (2023). Copper – supply in 2023 based on USGS (2024); supply in 2030 based on BNEF (2024b), ETC (2023) and S&P Global (2023). Phosphorous – supply in 2023 based on Brownlie *et al.* (2022) and USGS (2024); supply in 2030 based on IRENA analysis. Manganese – supply in 2023 based on USGS (2024); supply in 2030 based on Jupiter Mines (2023) and McKinsey (2022).

Notes: Supply estimates include announced, planned and potential supply. Lithium is expressed in terms of lithium carbonate equivalent (LCE). Copper refers to refined copper. The values for phosphorous refer to elemental phosphorous. Mt = million tonnes.

Both battery chemistry and battery size have a significant impact on the market dynamics of critical materials. Figure 2 features three graphs for each critical material. Each graph represents a different battery chemistry scenario. The graphs plot the potential market balance on the y-axis against various battery sizes on the x-axis. They showcase how each factor contributes to supply-demand relationships for critical materials. The average size of EV batteries, estimated to plateau at about 57 kilowatt hours (kWh), is crucial as it directly correlates with the demand for battery materials (BNEF, 2024a; Krishna, 2023). The sensitivity analysis depicted in Figure 2 considers a range of estimated supply and use colour coding: the yellow area indicates potential market shortfalls, while the green area highlights potential surpluses. Orange dots represent the market balance under conditions of low supply, while green dots denote the balance under high-supply scenarios.

LITHIUM

COBALT

GRAPHITE

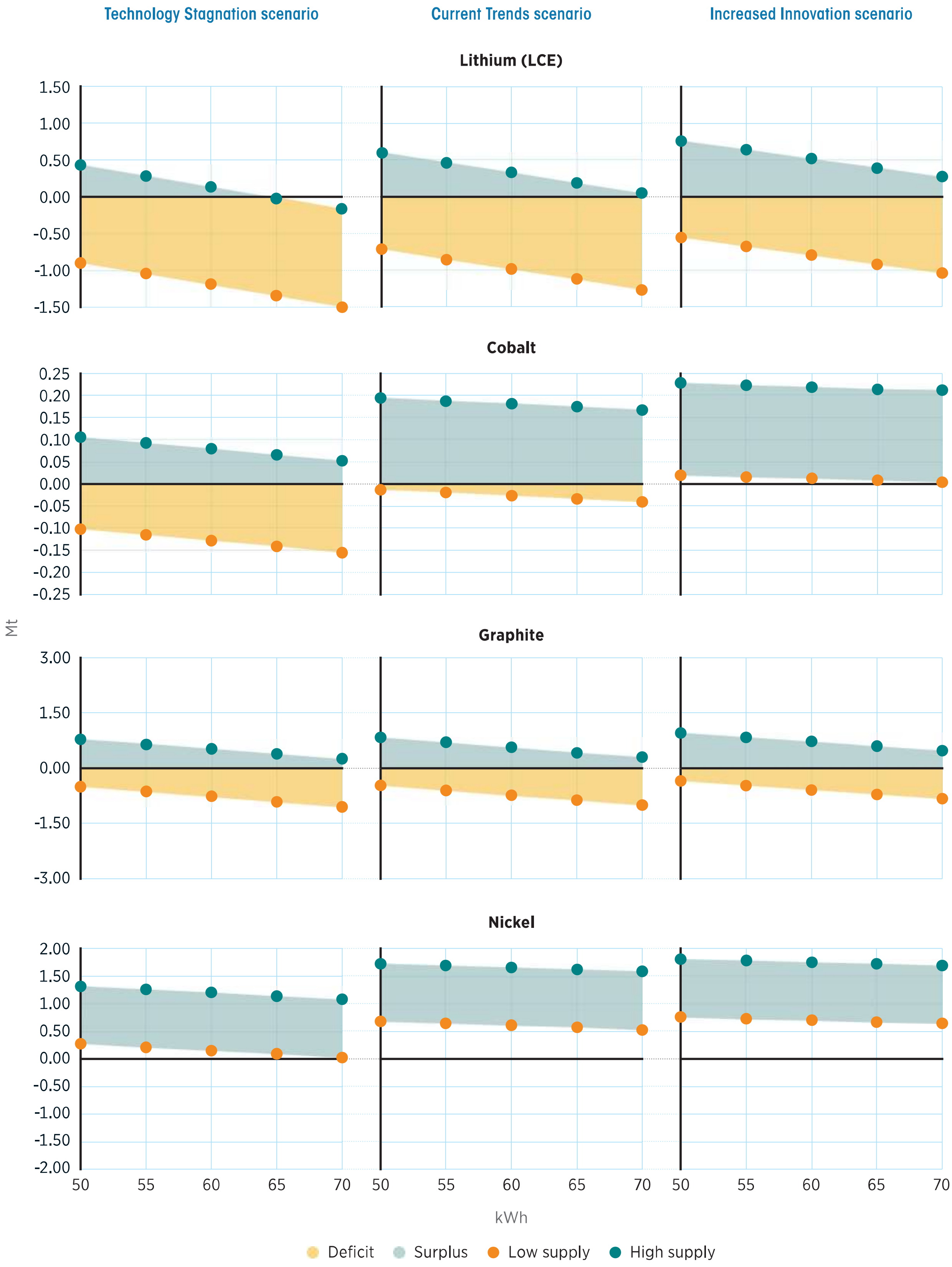
NICKEL

COPPER

PHOSPHOROUS

MANGANESE

FIGURE 2 Sensitivity analysis of supply-demand balance based on average battery size and battery chemistry



Notes: kWh = kilowatt hour; LCE = lithium carbonate equivalent; Mt = million tonnes.

Based on the analysis of factors affecting both supply and demand by 2030, the following perspectives are presented for each material:

- The demand for **lithium** remains largely unaffected by the choice of battery chemistry, since most EV battery technologies depend on it. Sodium-ion batteries, which do not rely on lithium, may enter the EV battery market later in the decade, but their impact on reducing lithium demand will likely be more significant after 2030. Long-term availability of lithium is not a constraint. Instead, addressing potential lithium deficits will significantly rely on expanding the supply chain or reducing demand through improvement of the energy density[2] of existing lithium-ion batteries.

- **Cobalt** can be substituted with the integration of technologies such as LFP and LMFP, rapidly reducing cobalt's criticality for road transport electrification. However, cobalt supply shortfalls could be possible in scenarios where cobalt-containing batteries, such as nickel manganese cobalt oxide (NMC) and nickel cobalt aluminium oxide (NMCA), remain widespread.

- Based on current supply projections, **natural graphite** will likely be insufficient to meet all expected graphite demand by 2030. **Synthetic graphite**, although more energy intensive, could be scaled up to bridge the supply gap. Beyond that, a transition towards anodes with increased silicon content is already occurring and could further reduce pressure on the material.

- **Nickel** demand has already been contained by the rise of LFP and LMFP batteries. A further transition from nickel-rich batteries to other chemistries would make supply shortages unlikely, unless the supply materialises at the lower end of the current supply projections range.

- The demand for **copper**, **phosphorous** and **manganese** from the EV market is expected to represent only a small share of global demand for these materials. Therefore, its impact on shaping supply and demand dynamics will be relatively minor compared with demand from larger sectors. However, addressing issues surrounding battery-grade purified phosphoric acid and high-purity manganese sulphate emerges as the most pressing concern, requiring concerted actions to rapidly expand their supply chains.

Innovation has already decreased the demand for critical materials significantly. For instance, LFP batteries, which had a single-digit market share in 2015, captured an estimated 44% of the passenger vehicle market in 2023. Projecting 2023's cobalt and nickel demand five years prior – considering the mix of battery chemistries at the time – would have led to significant overestimations of demand. For instance, cobalt and nickel demand from EV batteries would have been about 50% higher.

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[2] *In this report, energy density refers to gravimetric energy density.*

Advances in EV battery technology have also improved gravimetric energy density significantly, a 30% increase, on average, for battery cells and 60% for battery packs over the past decade (BNEF, 2024). These advances not only boost energy performance and drive down costs, they also play a significant role in reducing material demand. Further improvements are still possible. For instance, Contemporary Amperex Technology Co., Limited (CATL) and Northvolt have developed a sodium-ion battery with an energy density of 160 watt hour per kilogramme (Wh/kg); they are planning for the next generation to exceed 200 Wh/kg (CATL, 2023; Northvolt, 2023). Moreover, CATL has unveiled a condensed battery cell, which, through chemical and design innovation, is able to achieve a gravimetric energy density of 500 Wh/kg (CATL, 2023). This markedly surpasses the typical energy density of 250-300 Wh/kg in nickel-rich batteries (Ringbeck, 2024). Design presents another avenue for innovation. For example, BYD has commercialised the cell-to-pack technology and is now advancing to cell-to-body technology. This latest approach further increases energy density by integrating battery cells directly into a car's body, thereby completely eliminating the need for a traditional battery pack (BYD, 2023; WEF, 2023).

Innovation emerges as the central component in addressing potential bottlenecks, offering pathways to reduce demand and bolster supply. Among innovations, advancements in EV battery cathodes, notably LFP and LMFP, alongside emerging technologies, such as sodium-ion, could alleviate, if not entirely eliminate, the demand for some materials. Continuous improvement in energy density through innovative design and engineering could position LFP and LMFP as challengers to nickel-rich batteries' dominance in high-end EV market segments. Overcoming sodium-ion technology's challenges could lead to structural advancements, by partially or completely eliminating the need for some materials, for example, lithium, cobalt and graphite. Moreover, innovation in mining and processing could alleviate pressures on the supply side, enabling timely, cost-effective and sustainable production of materials.

This report details several actions for governments and stakeholders across the EV battery supply chain to ensure an adequate, reliable, sustainable and affordable supply of critical materials for EV batteries by 2030.

To address potential material bottlenecks, governments can play a key role in accelerating and supporting innovation aimed at reducing or eliminating the use of critical materials in EV batteries. Examples of possible innovations include advancements in cathode and anode technologies, and improvements in battery design and engineering to boost energy density and reduce material use. Given the rapid evolution of EV battery technologies, governments, mining and processing companies, and battery manufacturers can monitor markets closely and frequently and increase industry engagement to stay abreast of the latest trends and breakthroughs in innovation. Governments may also facilitate a reduction of critical material demand by supporting the accelerated deployment of EV charging infrastructure, supporting the adoption of EVs with smaller battery sizes, and thus lower material requirements.

Despite uncertainties in the estimated supply and demand of critical materials by 2030, ramping up supply will certainly be needed. Governments, in collaboration with key stakeholders, can mitigate supply-side risks by ensuring the timely expansion of supply through streamlined permitting processes and by making supply chains more resilient. This can be achieved by supporting industry stakeholders in diversifying the locations of their mining and processing activities; improving sustainability by adhering to the principles of a sustainable, just and fair energy transition; and addressing potential bottlenecks in the supply of often overlooked processed materials.

The energy transition requires strengthening international co-operation to leverage individual countries' strengths, acknowledging that no single country possesses all the materials and knowledge required for the transition. To enable informed decision making, governments, in collaboration with the private sector and international organisations, can enhance data quality and accessibility by developing unified databases, promoting data sharing and establishing harmonised data standards. Governments, supported by international organisations and industry stakeholders, can facilitate investment, knowledge sharing and capacity building to stimulate mining, processing and EV battery manufacturing in developing countries. This co-operation can help countries transition from merely increasing exports of mined critical materials to engaging in higher-margin activities such as material refinement and EV equipment manufacturing, ultimately enhancing economic benefits and making supply chains more resilient.

Potential also exists to boost secondary production and consumption by utilising stocks of recyclable and scrap materials already in circulation. This is particularly relevant for materials that have been used in large volumes across various industries for many years (*e.g.* copper and nickel). These actions may help mitigate supply chain bottlenecks to some extent by 2030. However, secondary production is not expected to become a major source of materials until the next decade, as technologies that use substantial quantities begin to reach their end of life. This is particularly relevant for lithium and cobalt, given the large-scale adoption of EVs in this decade has significantly increased their use, leading to higher volumes of recyclable materials. Innovation will lead to future batteries requiring fewer materials. Combined with advancements in recycling technologies, this means that when today's batteries are recycled, they will potentially yield more recoverable materials than are needed to produce new batteries. Governments can lay the groundwork for managing the large-scale recycling of EV batteries expected beyond 2030 by proactively designing circular economy policies to handle the anticipated high volumes of EV batteries reaching their end of life.

1. INTRODUCTION

The full decarbonisation of the world's energy systems will require significant quantities of so-called 'critical materials'[3] – a fact that has given room to concerns about the sufficiency of supply. As highlighted in previous IRENA publications and studies from other organisations, the resources to meet the cumulative material demand necessary for facilitating the global energy transition exist (ETC, 2023; Gielen, 2021; IRENA, 2021, 2023a). This is further highlighted in Table 1, which compares the estimated critical material demand in 2030 with the estimated identified resources.[4] Long-term availability is less of a concern than the capability to increase production rapidly enough to meet the growing demand in the short to medium term (Gielen, 2021).

TABLE 1 Overview of global resources for selected EV battery critical materials

Material	Estimated annual demand in 2030 (Mt/year)	Percentage of demand from EVs in 2030 (%)	Estimated resources (Mt)	Ratio of resources to their annual demand in 2030
Lithium	2.5-3.1	78-85	560	180-225
Cobalt	0.24-0.39	32-57	25[a]	65-105
Graphite	6.5-7.4	28-33	800	1 110-1 200
Nickel	3.9-4.7	13-24	350	75-90
Copper	31.3-38.1	3.5-4.2	2 100[b]	55-70
Phosphorous	28.2-29.2	2.2-3.2	30 000	1 030-1 060
Manganese	22.5-26.0	1.3-2.6	17 000	660-760

Based on: HalMan (2023) and USGS (2024).

Notes: a. In addition to the global terrestrial resources, more than 120 Mt of cobalt resources are found in deep-sea deposits.
b. Undiscovered copper resources amount to 3 500 Mt. EV = electric vehicle; Mt = million tonnes.

At present, the prevailing battery technologies rely on critical materials such as lithium, cobalt, nickel and graphite. By the end of 2023, the global installed capacity for manufacturing lithium-ion batteries was almost 2 000 GWh/year (Ratel Consulting, 2023). This is expected to more than triple by 2030, reaching over 7 300 GWh/year, with over 430 gigafactories in the pipeline (Benchmark Minerals Intelligence, 2022; Ratel Consulting, 2023; Ultima Media, 2022). This expected growth, paired with recent material supply squeezes, has raised questions about whether supply will be able to match demand by 2030.

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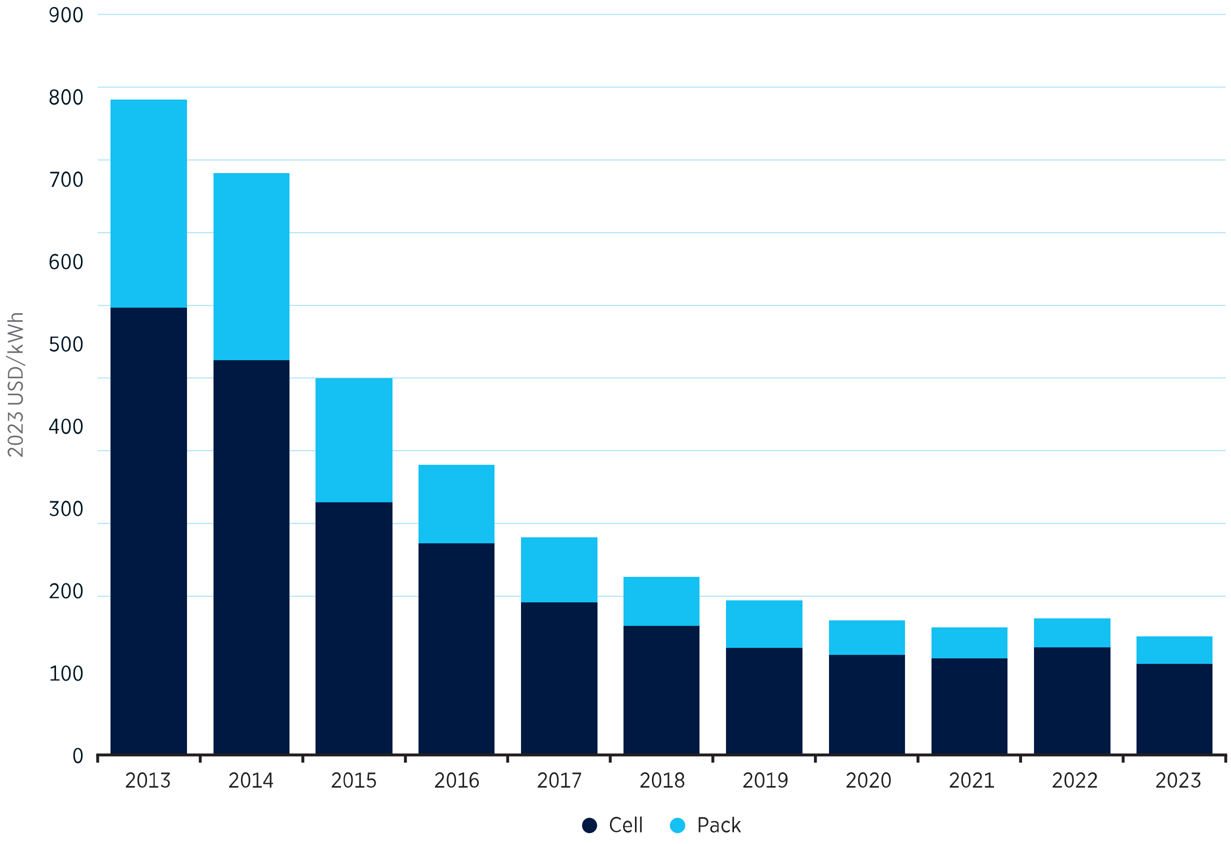
[3] *The term "critical materials" lacks a universally accepted definition. The criticality of materials can vary significantly depending on geographical location, and is typically characterised by factors such as scarcity, economic importance, the complexity of the extraction and refinement processes, and a lack of viable substitutes (IRENA, 2023a). In the context of this report, "critical materials" refers to metals, minerals and other elements essential for producing key technologies for the energy transition, such as EV batteries.*

[4] *Resources are the total estimated concentrations of metals or minerals with potential economic value, while reserves refer to the economically viable part of these resources.*

The world's ability to effectively extract and manage the critical materials needed for producing electric vehicle (EV) batteries will not only be crucial to ensure their sufficient supply and the timely decarbonisation of transport, it will also be instrumental in doing so at the lowest cost possible. Batteries are a major cost component of EVs, and material costs are the largest cost component of battery cells, typically accounting for about three-quarters of their total cost (Argonne National Laboratory, 2023).

Lithium-ion battery packs and cells have seen their prices drop to only a fifth of what they were a decade ago. This significant cost reduction has been driven by economies of scale, alongside innovations in new battery chemistries, and improvements in energy density. While battery prices have fallen drastically (see Figure 3), a shortage in the supply of critical materials, similar to what was already experienced in 2022 with cobalt and lithium, would result in cost increases. Existing long-term agreements between raw material producers and battery manufacturers could initially mitigate sudden price spikes. However, as these contracts are renewed, increased costs of these materials could ultimately impact battery producers. Persistent shortages could not only halt the declining trend of battery prices, but also unnecessarily delay the energy transition.

FIGURE 3 **Volume-weighted average price split for lithium-ion battery packs and cells, 2013-2023 (real USD 2023/kWh)**



Source: BNEF (2023a).
Note: kWh = kilowatt hour.

This study aims to provide an understanding of potential trajectories of critical material demand for 2030 in the context of the rapidly evolving EV market. It also aims to investigate how various factors, such as the adoption of different battery chemistries and sizes, affect the demand-supply balance for these materials.

The analysis is based on the outputs of IRENA's EV Battery Materials Demand Model, which explores three demand scenarios for critical materials used in EV batteries up to 2030 and how they compare to the expected critical material supply ranges found in literature.

The bulk of the analysis can be found in Chapter 2 of this document, which has three main parts:

- **Section 2.1** explores the role of EVs in the energy transition and the assumptions regarding EV deployment and related battery demand as per IRENA's *World Energy Transitions Outlook*.
- **Section 2.2** delves into the different aspects that affect the demand for EV battery materials and introduces IRENA's EV battery materials analysis.
- **Section 2.3** reviews the prospects of critical material supply and some of the factors affecting them.

Chapter 3 presents the main results from the supply and demand analysis and outlines strategic policy recommendations for navigating the evolving EV battery materials market to ensure adequate supply and timely decarbonisation.

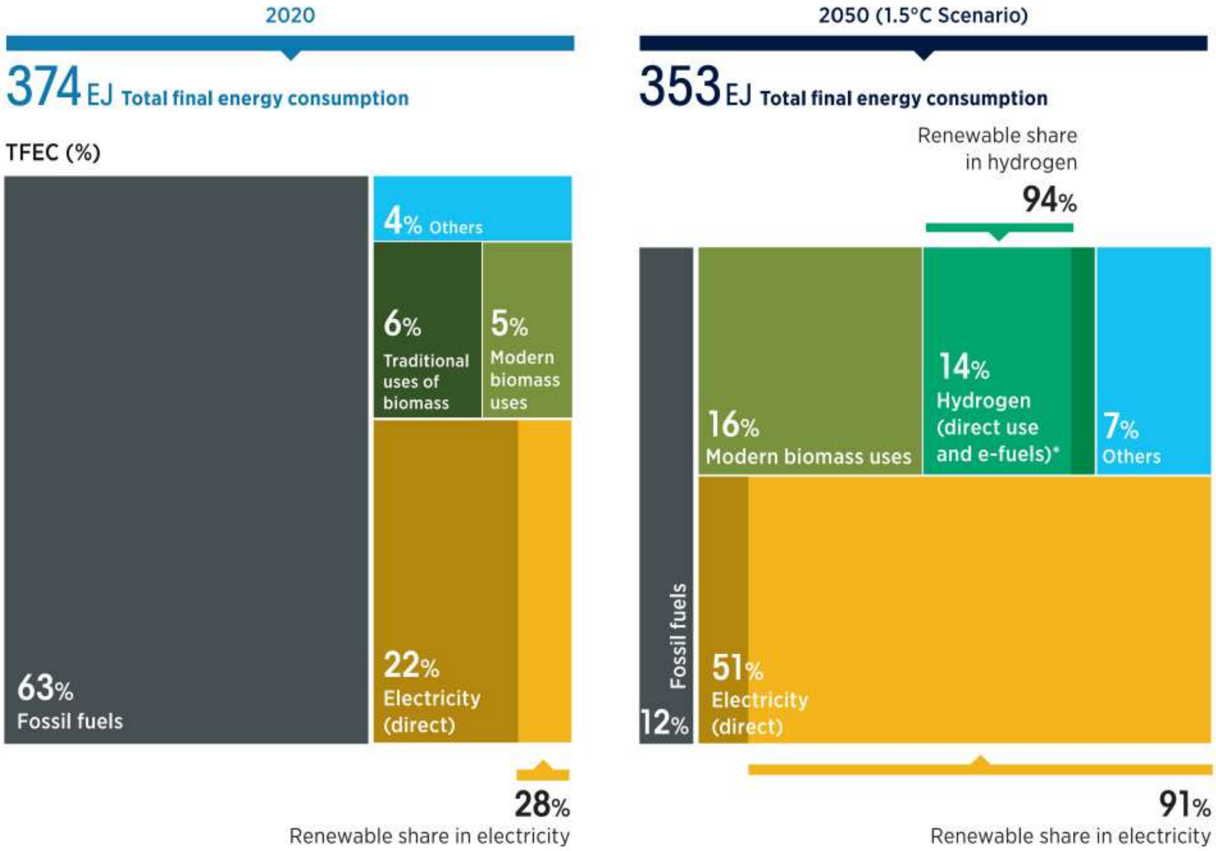
More detailed analyses of the supply-demand prospects for each critical material examined in this report can be found in Annex 1.

2. DEMAND–SUPPLY PROSPECTS FOR EV BATTERY MATERIALS

2.1 The role of electric vehicles (EVs) in the energy transition

The global energy transition will require profound changes in national energy systems. A key solution in this regard is the electrification of multiple energy services in end-use sectors, including buildings, transport and industry. Electricity consumption currently accounts for about 20% of total final global energy consumption (Figure 4) (IRENA, 2023b). By 2050, electricity would become the main energy carrier, constituting more than half of total final global energy consumption in a 1.5°C Scenario (IRENA, 2023b). This would lead global electricity demand to triple by 2050, with renewable sources meeting about 91% of that demand, according to IRENA's *World Energy Transitions Outlook* (IRENA, 2023b).

FIGURE 4 **Breakdown of total final energy consumption by energy carrier under the 1.5°C Scenario, 2020-2050**



Source: IRENA (2023b).

Notes: The figures above include only energy consumption, excluding non-energy uses. EJ = exajoule; TFEC = total final energy consumption.

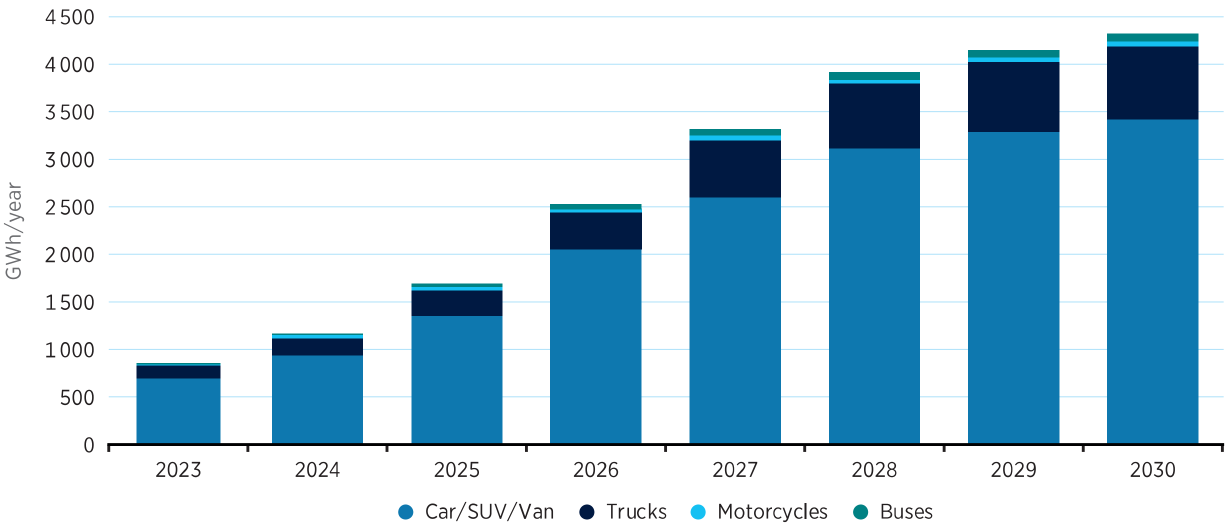
Road transport is a critical piece in the transport sector decarbonisation puzzle. It accounts for over three-quarters of all transport emissions, or a fifth of global energy-related emissions (IEA, 2021, 2023). Battery EVs have emerged in recent years as the key solution for the sector's decarbonisation. Rapid technological progress in EV batteries, enabled by significant performance improvements and cost reductions, has greatly improved their economic case. Such rapid technological progress is opening the door for their mass adoption in segments for which they were previously unsuitable, for example, long-haul freight road transport.

EV adoption is increasing exponentially; 14 million electric passenger cars were sold in 2023, equivalent to approximately 18% of global automobile sales and representing a 340% increase since 2020 (BNEF, 2024a; Carey, 2024; EV-Volumes, 2023). Staying aligned with IRENA's 1.5°C Scenario (IRENA, 2023b) would require global EV sales to continue growing to about 60 million vehicles per year by 2030.

The acceleration of EV adoption necessarily implies a sharp increase in the demand for EV batteries. While most of the unit EV sales consist of passenger cars and two wheelers, the demand for batteries will be mostly driven by passenger cars and trucks. This trend reflects the magnitude of passenger car unit sales, as well as the large battery sizes required for trucks.

Figure 5 shows EVs' battery demand as estimated in IRENA's 1.5°C Scenario. EV battery demand is expected to exceed 4 300 GWh per year by 2030, about a five-fold increase over 2023. Apart from EV battery demand, other applications also have growing battery requirements, namely, battery energy storage systems (BESS), whose demand is anticipated to grow six-fold over 2023-2030 (BNEF, 2023b). While the anticipated growth of BESS represents a substantial rise in battery demand, the demand for EV batteries is anticipated to be about ten times greater by 2030.

FIGURE 5 **Estimated battery demand for EVs under IRENA's 1.5°C Scenario by segment, 2023-2030**



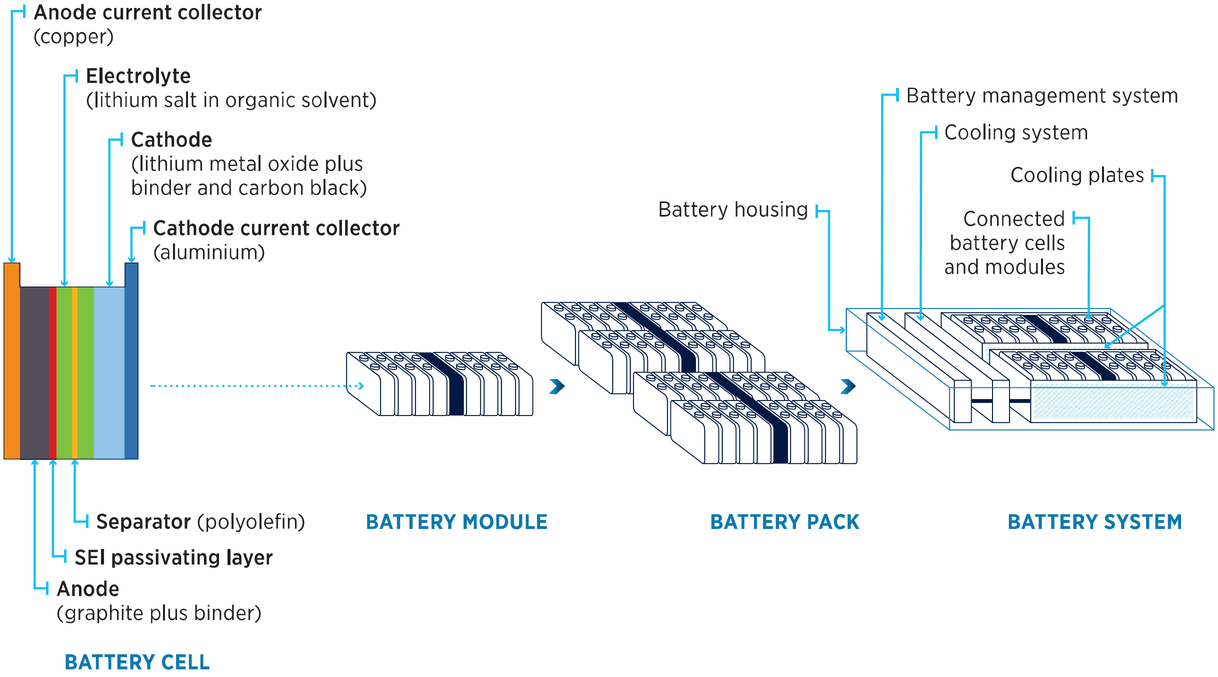
Notes: Includes battery EVs and plug-in hybrid EVs. GWh = gigawatt hour; SUV = sports utility vehicle.

2.2. Demand for EV battery materials

2.2.1. EV battery composition and chemistries

An EV battery, typically consisting of battery cells arranged in a battery pack, consists of an anode (commonly made of graphite), a cathode (often composed of lithium metal oxides) and an electrolyte (usually a liquid or solid lithium salt) (Figure 6). Together, these components facilitate the movement of lithium ions during charging and discharging cycles, enabling the storage and release of energy.

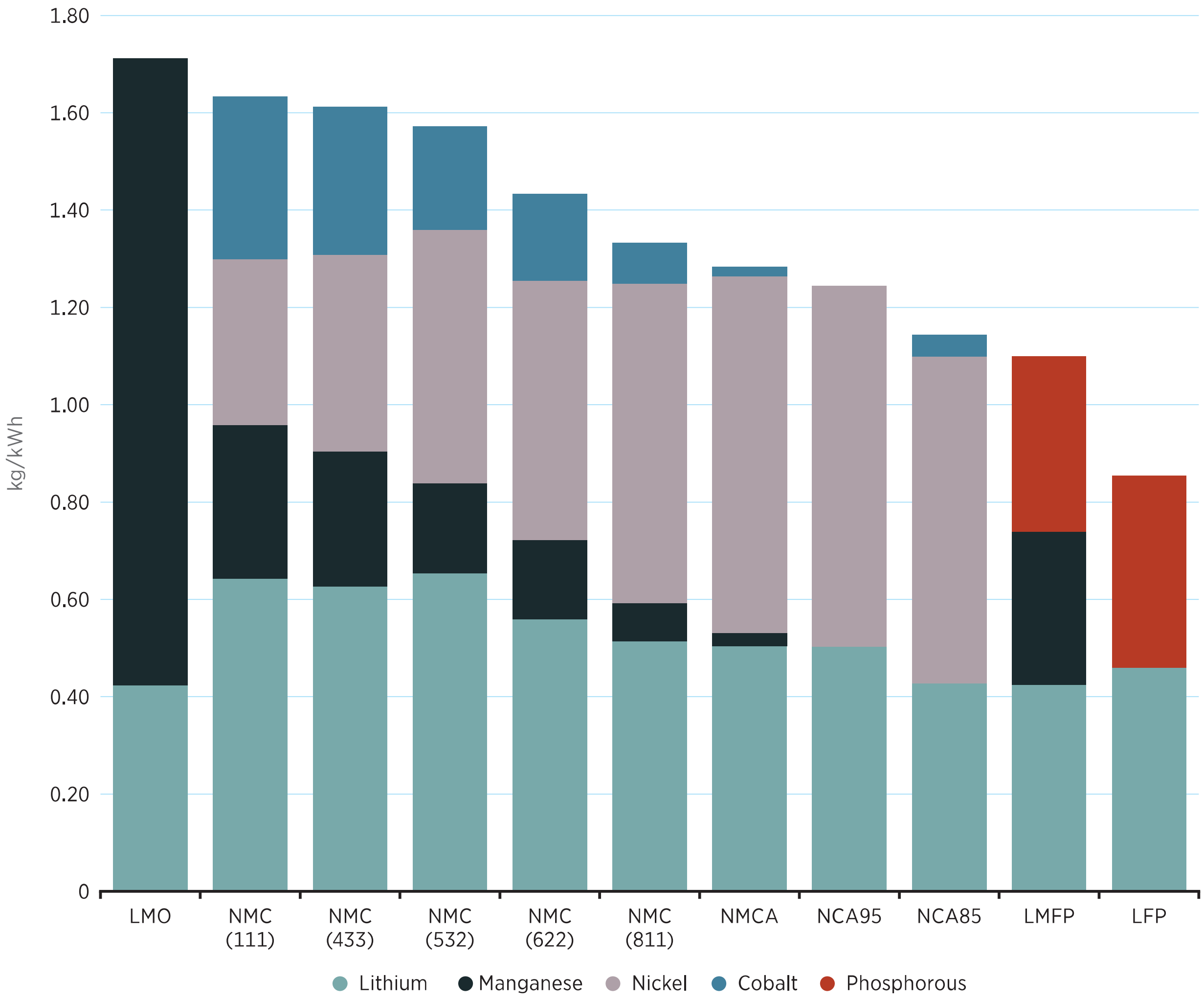
FIGURE 6 Battery system components and internal components of a battery cell



Source: Gaines *et al.* (2021).

The cathode and anode represent most of the critical material demand in an EV battery (Argonne National Laboratory, 2023). The most common EV cathodes include nickel manganese cobalt oxides (NMC), nickel cobalt aluminium oxides (NCA), nickel manganese cobalt aluminium oxide (NMCA), lithium iron phosphate (LFP) and lithium manganese iron phosphate (LMFP). While all these cathodes rely on lithium, the overall composition, including the types and amounts of materials used, varies significantly (Figure 7). For instance, NMC and NCA batteries use varying quantities of nickel and cobalt, while LFP and LMFP batteries use iron and phosphate as components.

FIGURE 7 Estimated average critical material metal content of selected lithium-ion EV battery cathodes



Source: Maisel *et al.* (2023).

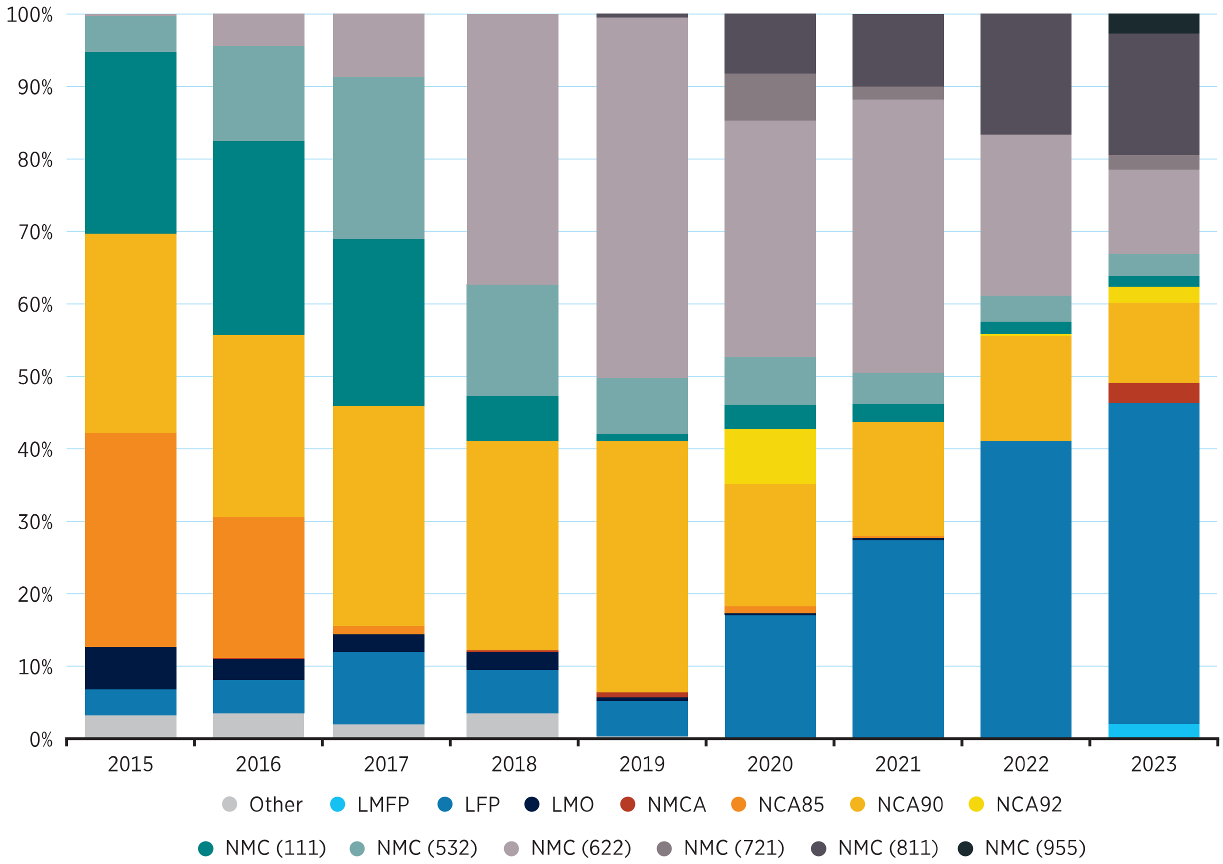
Notes: Lithium is expressed in terms of lithium carbonate equivalent (LCE). The numbers following the NCA nomenclature indicate the proportion of nickel in the NCA cathode chemistry, whereas the numbers following the NMC nomenclature indicate the relative proportions of nickel, manganese and cobalt in the cathode material. kg = kilogramme; kWh = kilowatt hour; LFP = lithium iron phosphate; LMO = lithium manganese oxide; NCA = nickel cobalt aluminium oxide; NMC = nickel manganese cobalt oxide; NMCA = nickel manganese cobalt aluminium oxide.

At present, the most common EV anode chemistry is pure graphite; it accounted for more than two-thirds of the market in 2023 (BNEF, 2024a). Graphite in EV batteries typically consists of a blend of natural and synthetic graphite, used in varying ratios depending on the required cost, performance and battery type (ECGA, 2023). About a third of the market is accounted for by silicon-graphite anodes, which blend graphite with silicon, typically with silicon representing 5%-15% of the blend (BNEF, 2024a). Besides graphite, copper is also widely used in EV battery anodes, since copper foils play an important role as current collectors in the anode (Argonne National Laboratory, 2023).

2.2.2. Historic evolution of the EV battery chemistry mix and the role of innovation

The cathodes of choice in the EV industry have evolved rapidly over the past few years (Figure 8). This transformation has been driven by innovation, which has reduced reliance on specific raw materials; improved energy performance; and made batteries safer, more durable and cost-effective. Three key trends are worth noting. First, nickel-rich batteries such as NMC and NCA batteries have dominated the market, although with decreasing market share, and still accounted for over half of the global market in 2023. Second, there has been a decline in cobalt and manganese content in NMC batteries, evidenced by the transition from NMC111[5] to NMC622 and NMC811. The gradual transition away from cobalt has predominately been driven by concerns regarding its cost and sustainability. Third, the adoption of LFP batteries has grown rapidly, from having a single-digit market share in 2015 to becoming a major chemistry in 2023, capturing about 44% of the passenger vehicle market (BNEF, 2024a).

FIGURE 8 Global EV battery cathode chemistry mixes for passenger vehicles, 2015-2023



Source: BNEF (2024a).

Notes: LFP = lithium iron phosphate; LMFP = lithium manganese iron phosphate; LMO = lithium manganese oxide; NCA = nickel cobalt aluminium oxide; NMC = nickel manganese cobalt oxide; NMCA = nickel manganese cobalt aluminium oxide.

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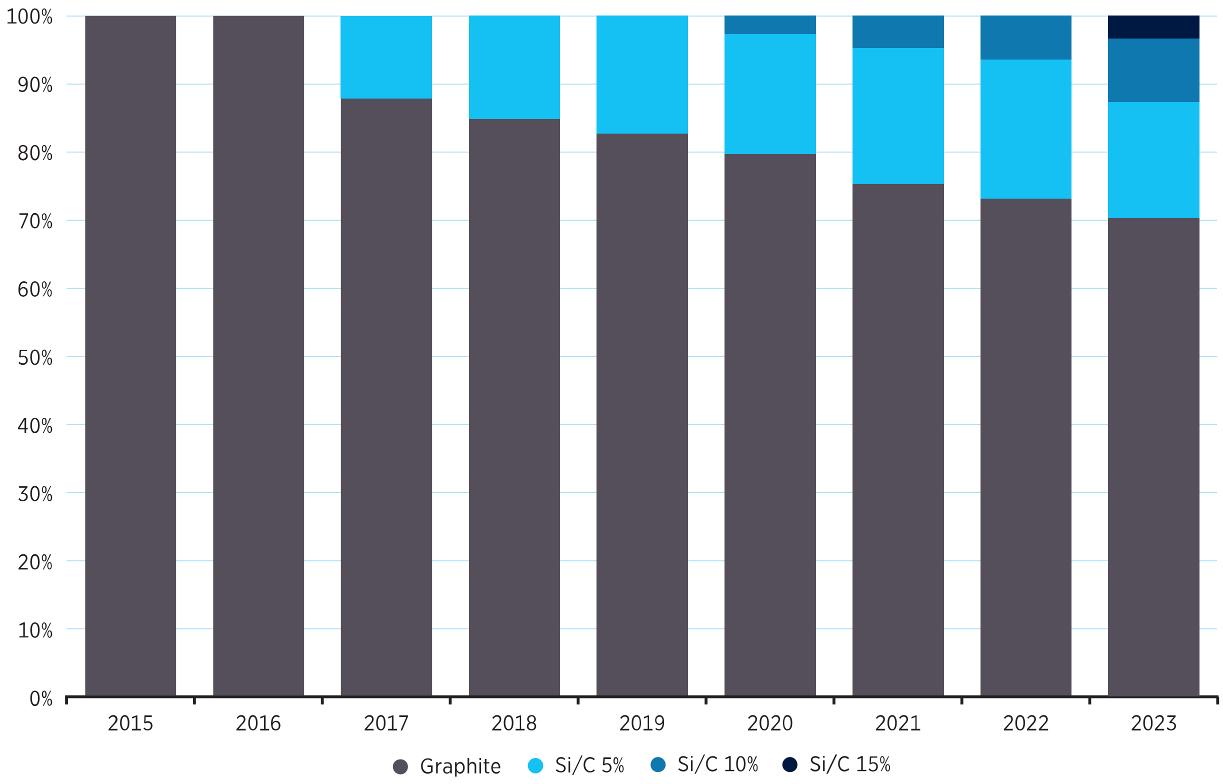
[5] *The numbers after NCA refer to the percentage of nickel in the cathode, whereas for NMC they refer to the metal ratio in the cathode, e.g. NMC (622) is 6 parts nickel, 2 parts manganese, and 2 parts cobalt, while NCA95 means the cathode is composed of 95% nickel.*

NMC and LFP/LMFP are expected to remain the most prevalent EV battery chemistries in this decade. However, uncertainty persists regarding the balance between them as well as regarding the penetration of other battery chemistries. Disruptive innovation, driven by efforts to reduce reliance on certain critical materials and lower costs, can alter the current trajectory. Notably, emerging battery technologies, such as sodium-ion – which had a planned production capacity of about 300 GWh/year for 2030 based on announcements made by 2023 – may increasingly penetrate the market towards the end of the decade (BMI, 2023).

The EV battery anode mix composition has also undergone significant evolution in the past decade (Figure 9). Pure graphite anodes, typically composed of natural and synthetic graphite, have long maintained dominance since the commercialisation of lithium-ion batteries. However, silicon-graphite composites, featuring progressively higher silicon content, or even pure silicon, could increasingly challenge graphite's dominance. Already, silicon-graphite composite anodes have captured a third of the market within five years (BNEF, 2024a). Technological advancements in silicon anode technology, alongside emerging alternatives such as lithium metal and hard-carbon anodes for sodium-ion batteries, could drive the future evolution of EV battery anodes resulting in reductions in graphite demand.

FIGURE 9 **Global EV battery anode chemistry mix, 2015-2023**

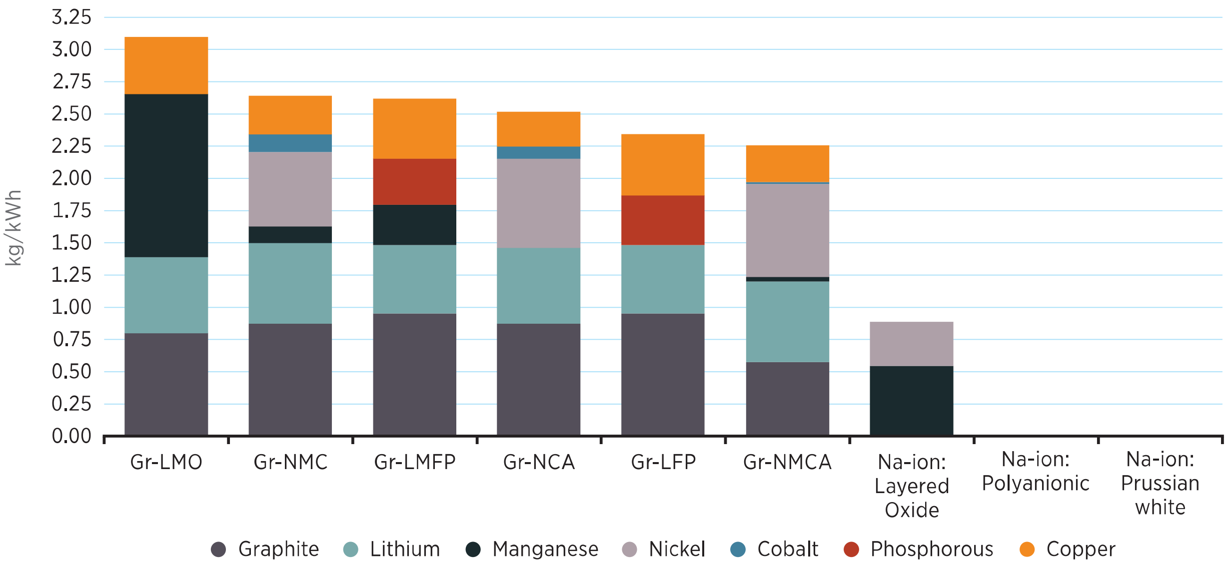


Source: BNEF (2024a).

Notes: Si/C refers to composite anodes composed of silicon and graphite; the percentage of silicon included in the composite material is specified.

EV batteries have varied material composition based on the chemistry, which mainly consists of anode and cathode materials, with additional consideration for copper used in the wiring and casing. Figure 10 shows the assumed average material composition for each EV battery chemistry type. From the figure, it is apparent that all chemistries except sodium ion rely on graphite and lithium. Lithium manganese oxide (LMO) stands out among these chemistries for requiring the largest quantity of critical materials; sodium-ion batteries require the least. However, LMO batteries, commonly used in motorcycles, have been losing popularity fast to LFP, which offers similar characteristics with fewer material requirements and a longer lifespan (Melancon, 2023; Porzio and Scown, 2021). Notably, LFP stands out with lower material requirements than NCA, NMC and LMO since it does not rely on cobalt, manganese or nickel.

FIGURE 10 **Estimated average critical material composition of selected EV battery packs**



Based on: Argonne National Laboratory (2022, 2024), Bernstein (2021) and Maisel *et al.* (2023).

Notes: The figure illustrates the material composition of various battery pack types. Each name denotes the specific combination of materials used for the anode and cathode. For instance, "Gr-NMC" signifies a battery pack whose composition consists of graphite as the anode paired with a nickel manganese cobalt (NMC) cathode. The material compositions for NCA and NMC are calculated using a weighted average, considering the market shares of each category. Gr = graphite; LFP = lithium iron phosphate; LMFP = lithium manganese iron phosphate; LMO = lithium manganese oxide; Na = sodium; NCA = nickel cobalt aluminium oxide; NMC = nickel manganese cobalt oxide; NMCA = nickel manganese cobalt aluminium oxide.

As shown in Figures 8 and 9, EV batteries have undergone significant innovation over the past decade. Projecting 2023's cobalt and nickel demand five years previous – considering the mix of battery chemistries back then – would have led to significant overestimations. For instance, cobalt and nickel demand from EV batteries would have been about 50% higher. Advancements in EV battery technology have also improved gravimetric energy density significantly: a 30% increase on average for battery cells and 60% for battery packs over the past decade (BNEF, 2024). These advancements not only boost energy performance and reduce costs, they also reduce the material demand.

The widespread adoption of LFP batteries also serves as a clear example of the rapid and transformative impacts of innovation. Praised for their safety, durability and cost-effectiveness, LFP batteries stand out for not requiring cobalt or nickel. While historically limited to entry-level vehicles due to its lower energy density compared with nickel-based chemistries, LFP has gained popularity due to the price volatility of materials such as cobalt and nickel. This shift is reflected in the market share of LFP batteries among passenger vehicles, which grew significantly from single digits in 2015 to about 44% in 2023 (BNEF, 2024).

Ongoing innovation in LFP batteries is effectively narrowing the energy density gap between LFP and NMC batteries. Further, the addition of manganese to LFP, resulting in LMFP, improves the batteries' energy density, positioning them in the middle between nickel-rich and LFP batteries. This development makes LFP and LMFP increasingly suitable for EV market segments currently dominated by NMC and NCA technologies.

However, innovation does not end there. Remarkable progress is underway, in both conventional lithium-ion batteries and emerging technologies, exemplified by sodium-ion, fluoride, zinc anode, lithium-metal and solid-state batteries, among others. These ongoing innovations hold the potential to not only reduce the demand for the materials in EV batteries but, in some cases, eliminate the need for some of them entirely.

Box 1: Sodium-ion batteries

Sodium-ion batteries are similar in design and construction to their lithium-based counterparts but rely on sodium compounds instead of lithium. Sodium is about a thousand times more abundant than lithium (National Library of Medicine, n.d.). Growth of this technology could therefore alleviate the short-term supply concerns and cost volatility that affect lithium.

Similarly, sodium-ion batteries employ hard carbon as an anode material, whereas lithium batteries rely on graphite. A graphite demand reduction due to increased penetration of sodium-ion batteries could help alleviate the supply concerns for this material while making it possible to reduce reliance on fossil feedstocks – since synthetic graphite is produced from fossil feedstocks, while hard carbon can be produced from biogenic feedstocks (Thompson *et al.*, 2021).

While sodium-ion batteries today have lower energy density than lithium-ion batteries, they also offer promising advantages, such as lower costs and safer operation due to their wider operating temperature ranges and better thermal stability (Zhao *et al.*, 2021).

Recently, manufacturers announced plans to deploy sodium-ion EVs and initiated the construction of sodium-ion facilities for commercial production in the beginning of 2024, signalling the rapid commercialisation of this battery technology (Kang, 2024).

Sodium-ion batteries show great promise and could become a good alternative for specific applications, for example, stationary storage and EV segments that do not necessarily require high energy density ranges. In this way, they can help alleviate supply chain bottlenecks in other segments and accelerate the energy transition. With further research and development, and the establishment of adequate supply chains, sodium-ion batteries could potentially compete with lithium-ion batteries, for example, LFP batteries.

2.2.3 Prospects for critical materials' demand from electric vehicles

To understand and explore potential critical material bottlenecks towards 2030, IRENA has developed a supply-demand analysis, which assumes a trajectory of EV technology diffusion aligned with the 1.5°C Scenario, equal to an estimated EV battery demand of about 4 300 GWh/year by 2030, as shown in Figure 5.

This projection considers the total EV sales and the estimated average battery size.[6] Drawing on current trends in passenger EV drivetrains, we assume that by 2030, battery EVs (BEVs) and plug-in hybrid EVs (PHEVs)[7] will represent, respectively, about 90% and 10% of the EV market (BNEF, 2024a). This represents a shift from current market shares of about 70% BEVs and 30% PHEVs (Rho Motion, 2023). The average battery size for passenger vehicles was calculated by combining the market share of BEVs and PHEVs, with their respective battery sizes. Based on this methodology, the estimated average battery size was 48 kWh in 2023, and it is estimated to increase to about 57 kWh by 2030. This increase is primarily driven by the growing share of BEVs, which typically have batteries four times larger than those in PHEVs (Argonne National Laboratory, 2022; BNEF, 2024a). Assumptions regarding the average battery size for other vehicle segments are provided in Annex 2.

We explore three scenarios for the evolution of the market shares of different battery chemistries (Figure 11):

- In a first scenario, named *Technology Stagnation*, limited innovation and a continued high share of nickel-rich chemistries is assumed.
- A second scenario, named *Current Trends*, represents the continuation of current innovation trends, dominated by increasing adoption of LFP and LMFP batteries.
- A third scenario, *Increased Innovation*, is characterised by an increase in LFP and LMFP and a significant rise in sodium-ion technology before the decade's end.

The battery chemistry mix varies by vehicle type depending on energy density, cost, and safety requirements. For instance, buses typically use LFP batteries for their safety and cost-effectiveness, while trucks tend to use nickel-rich batteries for their higher energy density, which is essential for long-range and heavy duty applications. The explorative scenarios for each vehicle category, which account for these variations in chemistry mixes, are detailed in Annex 2.

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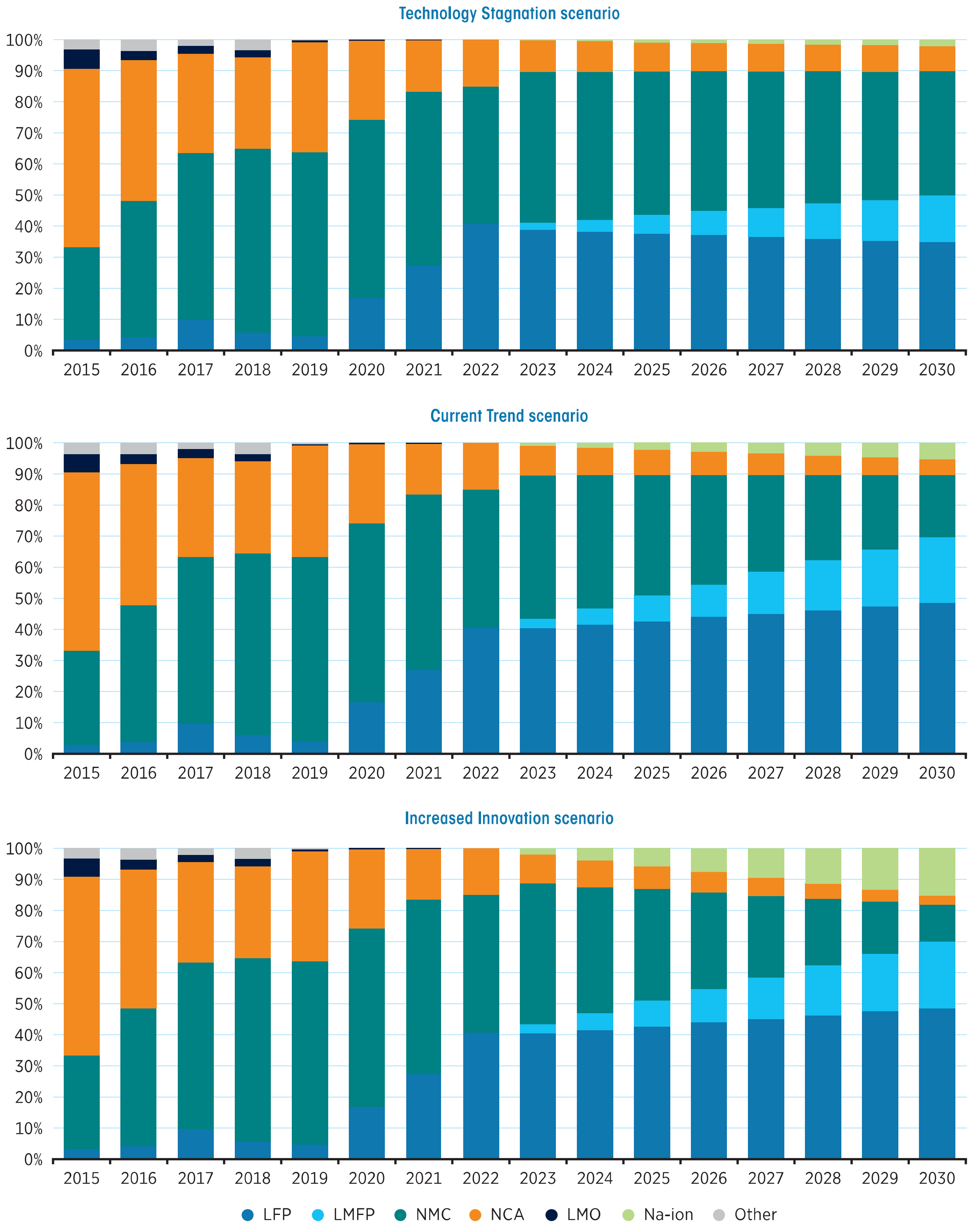
[6] *The global average battery size for passenger vehicles is calculated using a weighted average of the battery size for BEVs and PHEVs. This calculation includes their respective market shares of the EV market between 2022 and 2030. For other vehicle segments, the average battery size is estimated based on BEV data alone, due to limited data available.*

[7] *This analysis excludes hybrid EVs due to their reliance on fossil fuels.*

FIGURE 11 Evolution of historical battery chemistry market shares for passenger vehicles, 2015-2022, and explorative scenarios, 2023-2030



Notes: Considering the diverse variants within each battery type, simplifications are made: LFP includes LMFP; NCA encompasses variations such as NCA95, NCA92 and NCA90; NMC encompasses variants such as NMC (811), NMC (712) and NMC (522). LFP = lithium iron phosphate; LMFP = lithium manganese iron phosphate; LMO = lithium manganese oxide; Na-ion = sodium-ion; NCA = nickel cobalt aluminium oxide; NMC = nickel manganese cobalt oxide.

To estimate the material demand for EV batteries under various chemistry scenarios, we use material composition assumptions derived from other organisations (Argonne National Laboratory, 2022, 2024; BNEF, 2024a; Maisel *et al.*, 2024). The detailed material content for each battery chemistry is provided in Annex 2. The analysis also considered anticipated improvements in energy density, innovation for reducing graphite content in the anode,[8] and assumptions about the material requirements and market shares of various sodium-ion compositions.[9]

To ensure a comprehensive assessment of the total demand for the analysed materials, the demand from other sectors is also estimated. This relies on sector-specific historical growth rates and forecasts from other organisations.

The analysis shows that EV batteries only drive a fraction of the demand for critical materials. Among the seven materials analysed in this study, only lithium could be deemed industry centric for EV batteries (constituting 50% or more of the market share reliant on EV batteries) (Figure 12). Nonetheless, the analysis indicates a significant trend where demand from EVs represents a growing portion of the total demand for all materials between 2022 and 2030. For instance, the share of demand from EVs for lithium is estimated to grow to 78-85% by 2030, from 62% in 2022. For nickel, the share could rise to 13%-24% by 2030, from 8% in 2022, while for graphite, it could grow to 28%-33% by 2030, from 11% in 2022.

Most demand for critical materials is primarily driven by one or several other applications. For instance, most of the graphite and manganese demand by 2030 is estimated to originate from the steel industry; nickel demand from stainless steel applications; and phosphorus demand from fertiliser production. Copper demand is for construction and power-related infrastructure. The share of demand from EV batteries relative to the total demand is estimated to be approximately 4% for copper, about 2%-3% for phosphorous and about 1%-3% for manganese by 2030. Despite the relatively small demand for certain materials compared with their market size, concerns exist regarding the supply chains of battery-grade requirements. These include high-purity manganese sulphate for manganese and purified phosphoric acid for phosphorus. More information is provided in Annex 1.

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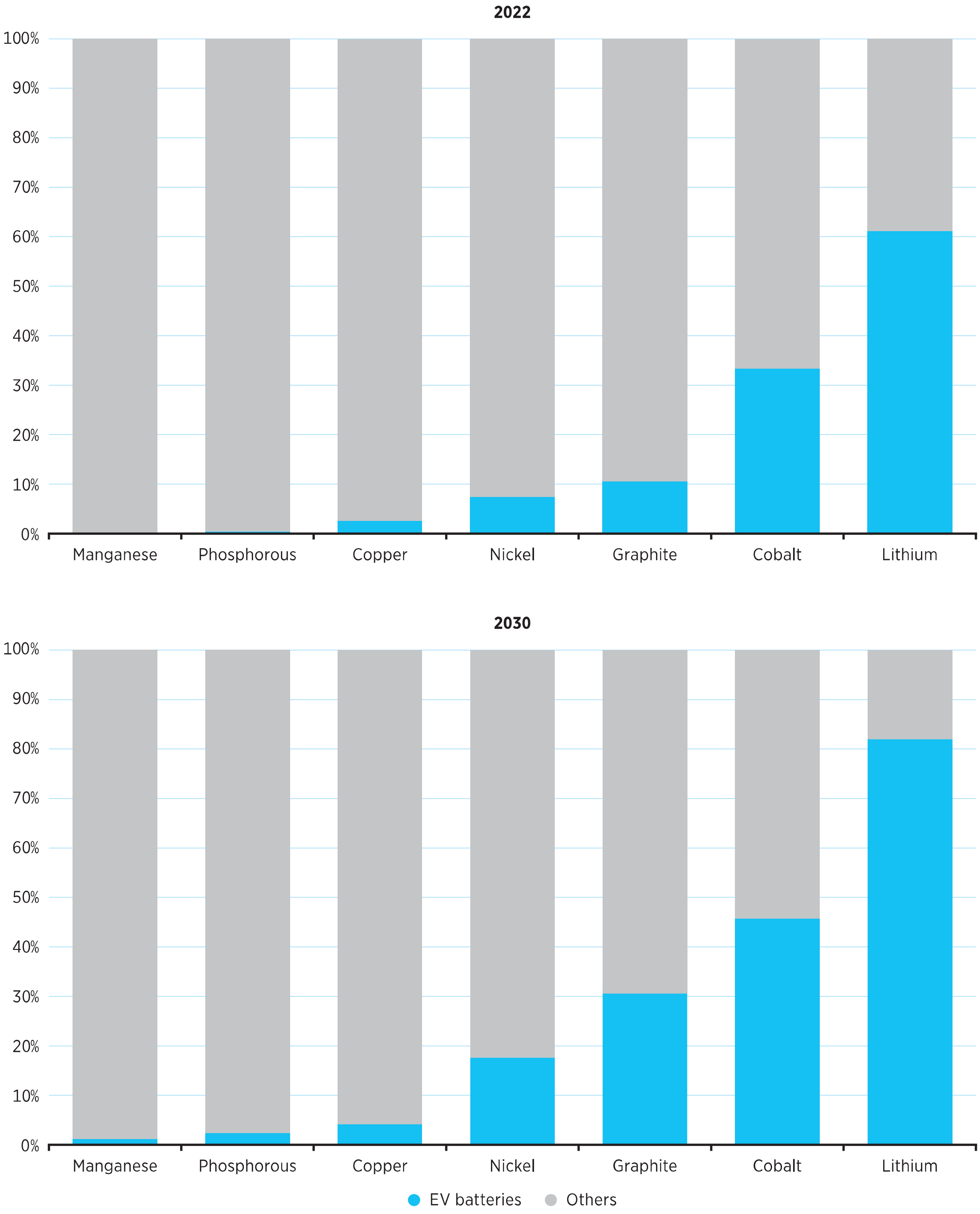
[8] *Current innovation trends in anode chemistry are assumed to continue towards 2030, including the increased share of silicon content and the emergence of new anode technologies such as pure silicon. Therefore, in line with forecasts from other organisations, we assume a reduction of about 25% in the graphite content of anodes in lithium-ion batteries across all scenarios by 2030 (BNEF, 2024a).*

[9] *The material composition for sodium ion represents a weighted average based on the assumption that by 2030, layered metal oxide technology will represent a 75% market share, polyanionic 15% and Prussian blue analogue 10% (Benchmark Minerals, 2023). Layered metal oxide technology can have numerous compositions, with differing material requirements. This study assumes the material composition of a layered metal oxide with a sodium nickel manganese magnesium titanate oxide cathode based on observed commercial developments (Gupta et al., 2022).*

FIGURE 12 Estimated global share of material demand from EV batteries and other applications, 2022 and 2030



Notes: The figure illustrates the estimated share of demand from EV batteries and other applications by providing an average estimate derived from IRENA's scenarios of EV battery demand and a range of estimates from other applications. More specifically, the range of demand from EVs per material in 2030 is estimated as follows: manganese (1.3%-2.6%); phosphorous (2.2%-3.2%); copper (3.5%-4.2%); nickel (13%-24%); graphite (28%-33%); cobalt (32%-57%); and lithium (78%-85%). EV = electric vehicle.

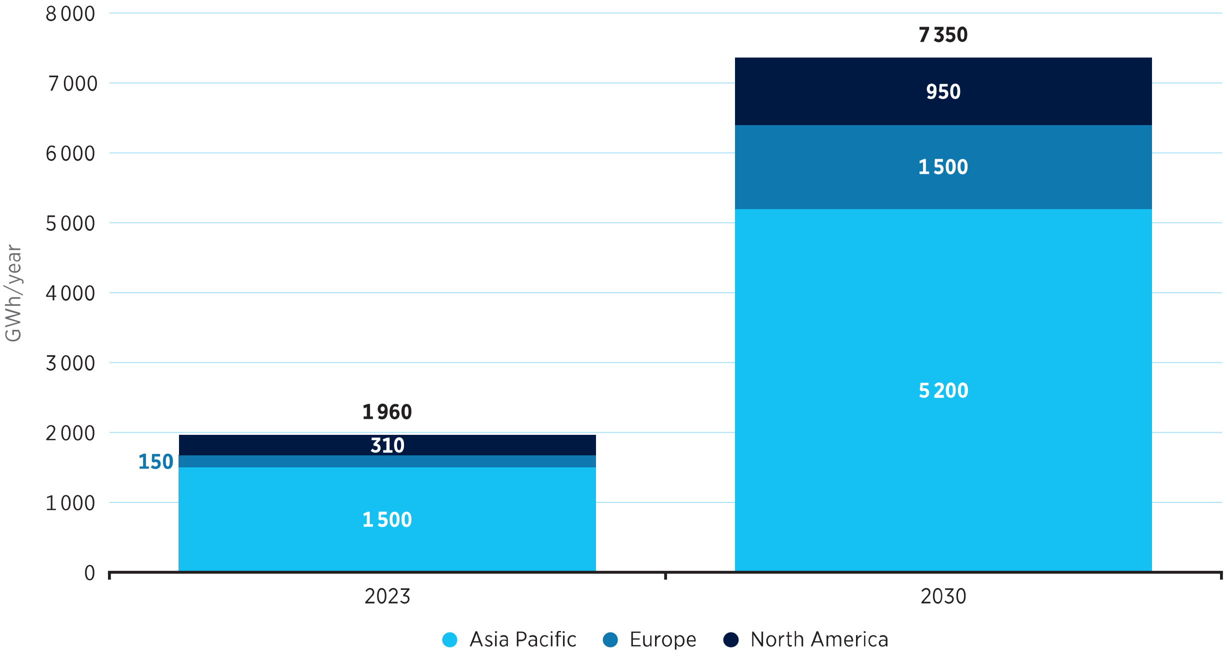
2.3 Supply of EV battery materials

2.3.1 Prospects for battery manufacturing capacity

The outlook for lithium-ion battery production capacity is positive, projected to grow more than three-fold, from 2 000 GWh/year in 2023 to 7 300 GWh/year by 2030 (Figure 13) (Ratel Consulting, 2023). This planned capacity would be sufficient to meet the 4 300 GWh/year demand from EV batteries in 2030, which IRENA estimates under a 1.5°C Scenario. Beyond 2030, a cumulative battery production capacity of 10 000 GWh/year has already been announced (Ratel Consulting, 2023).

It is important to note that these plans include commissioned, under-construction and announced projects, of which some are yet to reach a final investment decision. Moreover, this manufacturing capacity is not only to cater to EVs but also to meet the growing demand from other applications, such as stationary energy storage and portable electronics. The Asia-Pacific region currently accounts for about three-quarters of global lithium-ion battery manufacturing capacity (Ratel Consulting, 2023). Based on current plans, this share is expected to decrease to about 70% by 2030 (Ratel Consulting, 2023). Despite Asia-Pacific's continued dominance, capacity is expected to grow the fastest in Europe, a ten-fold increase over 2023-2030 (Ratel Consulting, 2023). In comparison, capacity in Asia-Pacific is projected to grow 250% and by 200% in North America (Ratel Consulting, 2023).

FIGURE 13 Regional lithium-ion battery manufacturing capacity in 2023 and planned capacity for 2030



Source: Ratel Consulting (2023).

Notes: The numbers represent lithium-ion battery capacity including batteries for applications other than EVs, for example, stationary energy storage and portable electronics. The figure does not include sodium-ion battery capacity.
GWh = gigawatt hour.

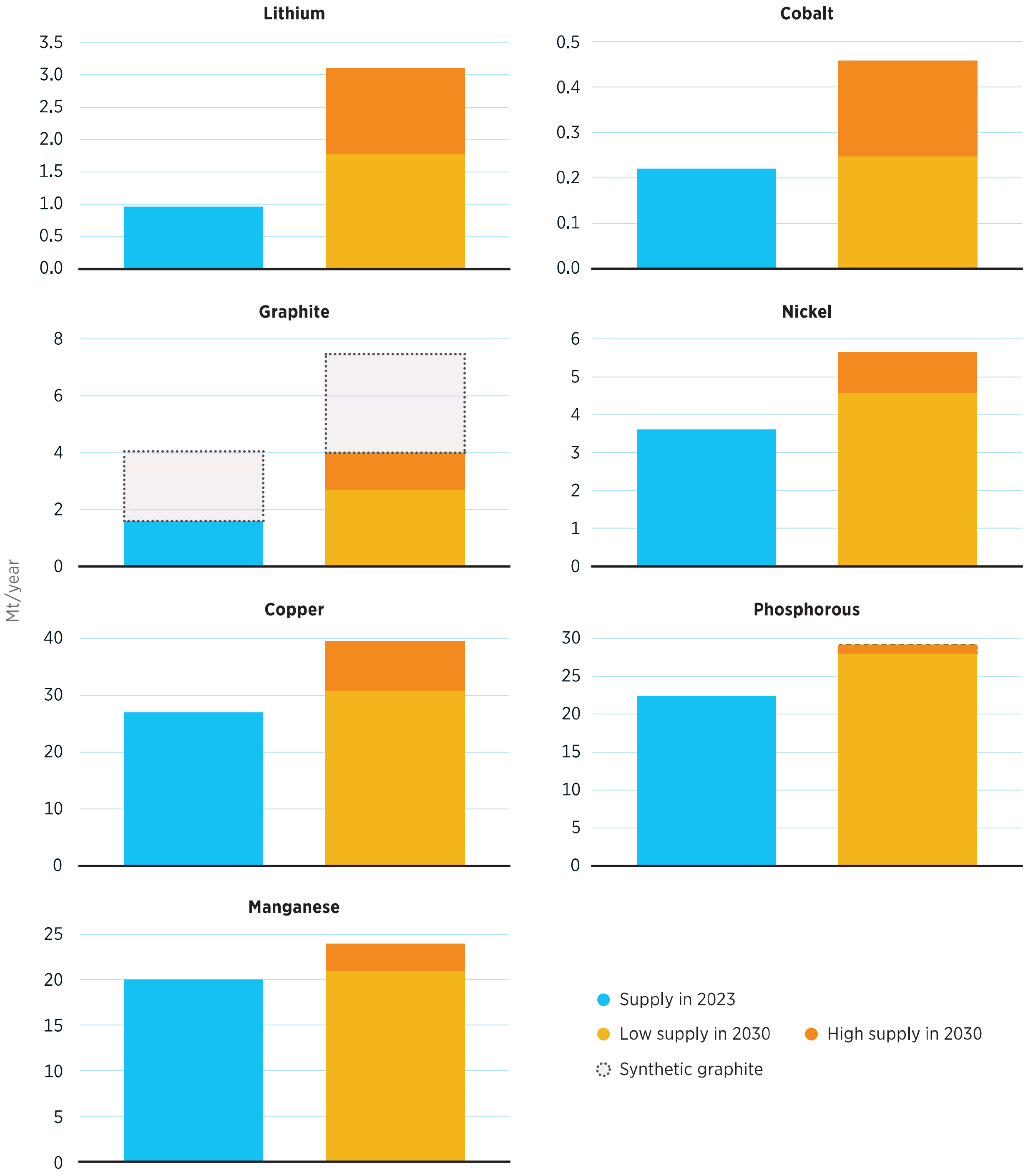
2.3.2 Prospects for critical material supply

Meeting IRENA's 1.5° C scenario would require a five-fold rise in EV battery production by 2030, as presented in Figure 5. To meet such demand from EV batteries, a proportional increase in raw material supply would be needed. To gauge the likelihood of a supply-demand gap, a range of current supply projections from other organisations are contrasted against the material demand estimated in IRENA's EV Battery Materials Demand Model. These projections include announced, planned and potential supply, including forecasts from academic literature, international organisations, the mining industry and market intelligence companies.

The analysis of existing projections shows substantial increases in supply for all materials from 2023 to 2030 (Figure 14). For instance, estimates of growth in lithium production range from 85% to 220% between 2023 and 2030, with forecasts indicating a potential increase from 1 Mt/year in 2023 to 1.8-3.1 Mt/year by 2030. Similarly, estimates of growth in nickel production vary from about 30% to 60% in the same period, with nickel supply potentially rising from 3.6 Mt/year in 2023 to 4.6-5.6 Mt/year by 2030. Likewise, estimates of growth in cobalt production range from about 15% to 110%, indicating a potential increase in cobalt supply from 0.22 Mt/year in 2023 to about 0.25-0.46 Mt/year by 2030.

While the supply of all materials is expected to grow significantly towards 2030, there is considerable uncertainty about how much of the potential supply will materialise. The projections have a wide range especially for lithium, cobalt and natural graphite, for which the difference between the highest and lowest supply estimates represents approximately 140%, 95% and 81% of the current supply, respectively. The actual levels of supply materialising by 2030 will largely depend on the market demand, technological innovation and regulatory frameworks. A more detailed overview per material can be found in Annex 1.

FIGURE 14 Material supply in 2023 and range of estimated supply in 2030



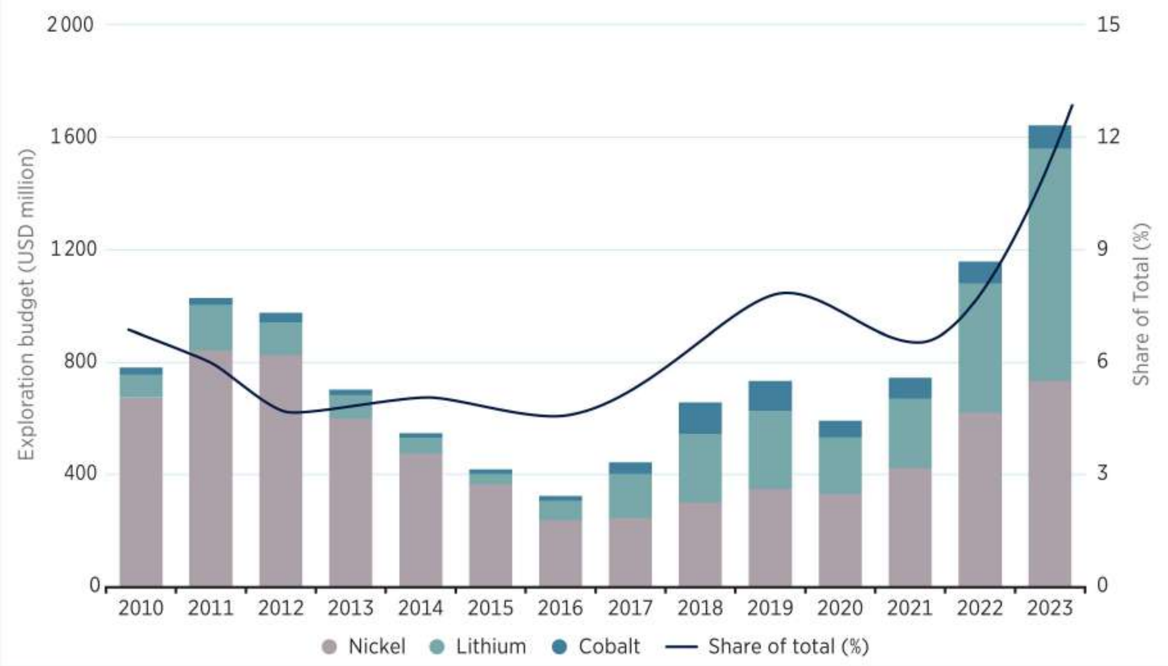
Sources: Lithium – supply in 2023 based on USGS (2024); supply in 2030 based on Albemarle (2023), BNEF (2024a), ETC (2023, 2023), Fitch Solutions (2022), Jimenez *et al.* (2022) and S&P Global (2023). Cobalt – supply in 2023 based on USGS (2024); supply in 2030 based on BNEF (2024a), Cobalt Blue Holdings (2022), Darbar (2022), ETC (2023, 2023), Fu (2020), Patterson *et al.* (2023), and S&P Global (2023). Graphite – supply in 2023 based on USGS (2024); supply in 2030 based on Black Rock Mining (2023), ETC (2023) and WSJ (2023). Nickel – supply in 2023 based on USGS (2024); supply in 2030 based on BNEF (2024b), ETC (2023, 2023) and S&P Global (2023). Copper – supply in 2023 based on USGS (2024); supply in 2030 based on ETC (2023, 2023), IHS Markit (2022), RFC Ambrian (2022) and S&P Global IQ (2022). Phosphorous – supply in 2023 based on Brownlie *et al.* (2022) and USGS (2024); supply in 2030 based on IRENA analysis. Manganese – supply in 2023 based on USGS (2024); supply in 2030 based on Jupiter Mines (2023) and McKinsey (2022).

Notes: Supply estimates include announced, planned and potential supply. A limitation of this harmonised supply forecast is that it compiles results from various organisations, companies and literature, each employing different methodologies and data sources. The values are expressed in contained metal. Lithium is expressed in terms of lithium carbon equivalent (LCE). Graphite supply does not include synthetic graphite. Copper includes refined copper. The values for phosphorous refer to elemental phosphorous. Mt = million tonnes.

Box 2: Historic investments in exploration

Mining exploration budgets refer to the funds allocated for the exploration and discovery of new material deposits or reserves. They often offer valuable insights into potential future material supply and mine development locations. While investment in mining exploration has decreased industry wide over the past decade (Dela Cruz, 2023), the growing demand for materials essential to the energy transition has led to increased exploration of key resources for electric vehicle batteries, such as cobalt, lithium and nickel. Exploration expenditures for these materials reached an all-time high in 2023 (Figure 15) (Dela Cruz, 2023).

FIGURE 15 **Total battery material exploration expenditure, 2010-2023 (real 2023 USD million)**



Source: De la Cruz (2023).

Much of the increase in exploration budgets for battery materials can be attributed to lithium. In 2023, lithium exploration budgets increased by about 80%, making it the third-most-explored commodity globally, only after copper and zinc. This momentum on exploration for EV battery materials may slow down in the short term due to price corrections resulting from anticipated surpluses (Dela Cruz, 2023). Nevertheless, sustained investment in exploration is expected due to anticipated medium-term supply deficits. In addition, diminishing quality of deposits means larger exploration budgets are needed to find high-quality deposits (Keen, 2022).

There is a role for innovation in the development of more sophisticated exploration methods, which have the potential to not only reduce exploration costs but also facilitate the discovery of new, high-quality deposits, thus addressing the industry's persistent challenges. Examples of these methods include the increased use of artificial intelligence, robotics and remote sensing (CORDIS, 2022).

3. KEY CONSIDERATIONS FOR POLICY MAKERS

3.1. Results and conclusions

With sustainable expansion of material supply chains along with continued innovation in battery chemistries, countries can meet the growing demand for EV battery materials. This is possible even under a very fast adoption of EVs, in line with a 1.5°C decarbonisation pathway (Figure 16). A critical factor will be the scale-up of material supply in line with currently available forecasts. Beyond that, faster adoption of innovative batteries with lower critical material requirements, for example, LFP, LMFP, and sodium-ion batteries, could further mitigate potential shortages for some materials, even if mining does not scale up as rapidly as expected. A broad range of outcomes is possible depending on the evolution of material supply capacity and the effects of technology innovation. For instance, lithium potential surpluses are estimated at 0.6 Mt/year, or about 25% of the estimated demand in 2030, while shortages could reach up to 1.3 Mt/year, representing over 40% of the estimated demand in 2030. An in-depth supply-demand analysis of each material can be found in Annex 1.

The results for the three exploratory battery chemistry scenarios (see Table 2) show that the demand for most critical materials, especially those for which EV batteries represent a large share of their total global demand by 2030, decreases in the Increased Innovation scenario. For instance, the cobalt demand in the Increased Innovation scenario is nearly a third of cobalt demand in the Technology Stagnation scenario, while the nickel demand is halved. To a lesser extent, the demand for graphite and lithium is also lower by about 10% and 15%, respectively, in the Increased Innovation scenario. The demand for manganese and phosphorus is substantially higher in the Increased Innovation scenario. However, the EV-driven demand for these materials represents only about 1%-3% of their total market, thus having a limited impact on the overall supply and demand dynamics for those raw materials.

TABLE 2 Overview of critical material demand from EV batteries by scenario, 2030 (Mt/year)

Material	Technology Stagnation	Current Trends	Increased Innovation
Lithium	2.47	2.27	2.06
Cobalt	0.22	0.12	0.08
Graphite	2.21	2.16	2.01
Nickel	1.10	0.62	0.53
Copper	1.32	1.39	1.33
Phosphorous	0.63	0.88	0.90
Manganese	0.35	0.37	0.51

Note: Mt = million tonnes.

FIGURE 16 Critical material supply and demand in 2023 and 2030

Sources: Lithium – supply in 2023 based on USGS (2024); supply in 2030 based on Albemarle (2023), BNEF (2024a), ETC (2023, 2023), Fitch Solutions (2022), Jimenez *et al.* (2022) and S&P Global (2023). Cobalt – supply in 2023 based on USGS (2024); supply in 2030 based on BNEF (2024a), Cobalt Blue Holdings (2022), Darbar (2022), ETC (2023, 2023), Fu (2020), Patterson *et al.* (2023), and S&P Global (2023). Graphite – supply in 2023 based on USGS (2024); supply in 2030 based on Black Rock Mining (2023), ETC (2023) and WSJ (2023). Nickel – supply in 2023 based on USGS (2024); supply in 2030 based on BNEF (2024b), ETC (2023, 2023) and S&P Global (2023). Copper – supply in 2023 based on USGS (2024); supply in 2030 based on ETC (2023, 2023), IHS Markit (2022), RFC Ambrian (2022) and S&P Global IQ (2022). Phosphorous – supply in 2023 based on Brownlie *et al.* (2022) and USGS (2024); supply in 2030 based on IRENA analysis. Manganese – supply in 2023 based on USGS (2024); supply in 2030 based on Jupiter Mines (2023) and McKinsey (2022).

Notes: Supply estimates include announced, planned and potential supply. Lithium is expressed in terms of lithium carbonate equivalent (LCE). Copper refers to refined copper. The values for phosphorous refer to elemental phosphorous. Mt = million tonnes.

The ranges of critical material demand from EV batteries shown in Table 2 are combined with the range of estimated critical material demand from other applications to create a range of estimated total demand for these materials by 2030. To assess the market balance for each material, we compare this estimated total demand with supply forecasts. More specifically, the potential surplus is calculated by comparing the lowest estimated demand with the highest estimated supply. Meanwhile, the potential deficit is assessed by comparing the highest estimated demand with the lowest estimated supply expansion. Table 3 provides an overview of supply and demand within these ranges, detailing the market balances and contextualising these figures in relation to estimated consumption levels.

TABLE 3 Overview of overall supply-demand balance estimations

Material	Overall demand in 2030 (Mt/year)	Supply in 2030 (Mt/year)	Estimated balance in 2030 (Mt)	Surplus/deficit relative to consumption (%)
Lithium	2.5-3.1	1.8-3.1	-1.3 to 0.6	25% surplus to 42% deficit
Cobalt	0.24-0.39	0.25-0.46	-0.14 to 0.22	94% surplus to 35% deficit
Graphite	6.5-7.4	6.2-7.5	-1.2 to 1	15% surplus to 16% deficit
Nickel	3.9-4.7	4.6-5.7	-0.1 to 1.7	44% surplus to 2% deficit
Copper	31.3-38.1	31.0-39.5	-7.2 to 8.2	26% surplus to 19% deficit
Phosphorous	28.2-29.2	28.0-29.2	-1.2 to 0.9	3% surplus to 4% deficit
Manganese	22.5-26.0	21-24	-5.0 to 1.5	6% surplus to 19% deficit

The analysis indicates that the potential supply of each material assessed can meet the demand in 2030, even in a 1.5°C Scenario. This includes graphite, through the use of synthetic graphite production, detailed in Annex 1.3. Supporting these findings, the analysis reveals potential surpluses for several key materials. For example, there could be a surplus of up to 94% relative to demand for cobalt, 25% for lithium and 44% for nickel. These potential surpluses could be available if supply is expanded to match the highest estimates and innovative technologies, such as LFP, LMFP and sodium-ion batteries, are rapidly adopted.

However, deficits remain possible if supply expansion matches the lowest estimates available and innovation lags. Significant deficits could occur, with potential shortages of about 20% relative to demand for materials such as copper and manganese, about 35% for cobalt, and up to 40% for lithium. On the other hand, even under these circumstances, nickel and phosphorus could experience relatively minor shortfalls, with each representing less than 2% and 4% of the market demand, respectively.

Overall, the long-term availability of resources for all materials is deemed adequate to support the energy transition, as shown in Chapter 1, where the demand estimates for 2030 are compared with identified resources. Nonetheless, concerted efforts are required to ensure a balanced market in the short-term. Each material features distinct characteristics in terms of supply constraints, substitution potential and the extent to which EV batteries are likely to influence its demand. Detailed information on these characteristics for each material can be found in Table 4.

For instance, while copper, phosphorous and manganese are needed for EV batteries, their market dynamics are predominantly driven by other industries. Policies, and efforts to reduce their demand specifically in EV batteries, would therefore have a limited effect on their overall market balance. This emphasises the need for a broader approach to resource management for these materials across all industries.

In contrast, demand for lithium and cobalt, and to an important extent also graphite and nickel, is substantially driven by EV batteries. The analysis of results shows that lithium is more critical for EV batteries than nickel and cobalt, where substitution is already possible with LFP and LMFP batteries. Natural graphite also faces significant supply constraints, but synthetic graphite, although more energy intensive, could be scaled up to bridge the supply gap. Beyond that, a transition towards anodes with increased silicon content is already occurring and could further reduce pressure on the material.

Nonetheless, while the global demand for some materials, such as phosphorous and manganese, is minimally affected by EV batteries, the production of their derivatives, such as purified phosphoric acid and high-purity manganese sulphate, is crucial and requires scaling up production to meet demand.

TABLE 4 Overview of key materials

Material	Overview
Lithium	The demand for lithium remains largely unaffected by the choice of electric vehicle (EV) battery chemistry, since most EV battery technologies depend on it. Sodium-ion batteries, which do not rely on lithium, may enter the EV battery market later in the decade, but their impact on reducing lithium demand will likely be more significant after 2030. Long-term availability of lithium is not a constraint. Instead, addressing potential lithium deficits will significantly rely on expanding the supply chain or increasing the energy density of existing lithium-ion batteries.
Cobalt	Cobalt usage can be substituted with the integration of technologies such as lithium iron phosphate and lithium manganese iron phosphate, rapidly reducing its criticality for road transport electrification. However, cobalt supply shortfalls could be possible in scenarios where cobalt-containing batteries (*e.g.* nickel manganese cobalt oxides and nickel cobalt aluminium) remain widespread.
Graphite	Based on current supply projections, natural graphite will likely be insufficient to meet all expected graphite demand by 2030. Synthetic graphite, although more energy intensive, could be scaled up to bridge the supply gap. Beyond that, a transition towards anodes with increased silicon content is already occurring and could further reduce pressure on the material.

Material	Overview
Nickel	Nickel demand has already been contained by the rise of lithium iron phosphate batteries, and supply has expanded rapidly, particularly in Indonesia. Further transition from nickel-rich batteries to other chemistries would make supply shortages unlikely, unless supply materialises at the lower end of existing projections.
Copper	While EV batteries contribute a small share of the total copper demand, exploring opportunities in other sectors, such as power (*e.g.* substituting copper with aluminium in the electricity grid), is also essential. Avoiding copper supply shortfalls is feasible through strategic initiatives, for example, rapidly developing or expanding copper mines and improving copper recovery from secondary sources. These efforts demand significant investments and the establishment of supportive regulatory frameworks to facilitate growth.
Phosphorous	Phosphorus demand from EV batteries is expected to account for only 2%-3% of the total global demand. However, addressing issues surrounding the supply of battery-grade purified phosphoric acid emerges as the most pressing concern, requiring concerted actions to rapidly expand its supply chains.
Manganese	EV batteries are expected to account for only about 1%-3% of the total manganese demand. Therefore, their impact on shaping manganese supply and demand dynamics will be relatively minor compared with larger sectors, such as steelmaking. When considering manganese for EV batteries, the concern is not primarily about the availability of raw manganese ore, but the unmatched demand for high-purity manganese sulphate (HPMS). Efforts to ramp up HPMS production will therefore be crucial to support the mass deployment of EVs by 2030.

The supply-demand results shown in Table 3 present significant uncertainties regarding future market balances. On the demand side, uncertainty stems from innovations in EV battery chemistries. To effectively adapt to the rapidly evolving EV battery landscape, policy makers and the mining industry should closely monitor market and technological developments and strengthen engagement with stakeholders across the industry. On the supply side, uncertainty stems from various factors, including fluctuating demand due to technological innovation, geopolitical tensions, resource nationalism, export restrictions and adjustments in regulatory frameworks.

Despite these uncertainties, supply will certainly have to be ramped up. As highlighted in Chapter 2.3, even the lowest demand estimates require significant increases in material supply by 2030. For instance, relative to levels in 2023, lithium supply would need to increase by up to 160%; graphite supply would have to increase by about 60%; refined copper by about 13% and manganese and nickel by about 10%. If demand exceeds these minimal estimates, then the actual increases in supply could be substantially higher.

Innovation has already significantly contributed to reducing critical material demand. This progress is underscored by notable advancements in energy density and the evolution of battery technology. For instance, trends in NMC oxide and NCA batteries over the past decade showcase efforts for reducing the cobalt demand. Moreover, the rapid emergence of batteries such as LFP and LMFP batteries has reduced the criticality of cobalt in road transport. Additionally, advancements in anode technologies, particularly those incorporating silicon, have played a crucial role in reducing reliance on graphite.

The findings underscore that further innovation, as examined through the three scenarios, along with underlying assumptions about improvements in energy density and innovation in the anode, can significantly reduce material demand and mitigate supply bottlenecks. This is especially relevant for those materials used most in EV batteries.

Looking towards 2030, innovation emerges as a central component in addressing potential bottlenecks. With energy density enhancements using innovative design and engineering, batteries with lower material requirements, such as LFP batteries, could emerge as challengers to the dominance of nickel-rich batteries. Specifically, LMFP batteries, with its higher energy density than LFP batteries, could pose a challenge to nickel-rich batteries in high-end EV market segments. Further, overcoming the technical challenges associated with sodium-ion technology could pave the way for its widespread commercialisation by this decade's end. Advancements in this technology could potentially reduce or eliminate the need for materials such as lithium, cobalt and graphite.

Moreover, innovation in mining and processing could alleviate pressures on the supply side and facilitate improved resource recovery, as well as timely, cost-effective and sustainable production of materials.

3.2. Recommendations for policy makers

The report details several actions for governments and stakeholders across the EV battery supply chain to ensure an adequate, reliable, sustainable and affordable supply of critical materials for EV batteries by 2030. This includes accelerating innovation in EV battery technologies to curb material demand, scaling up material mining and processing while adhering to the highest environmental, social and governance standards, increasing international co-operation in key areas such as improving data transparency and facilitating investment and technology diffusion, and establishing the groundwork for critical material recycling beyond 2030.

Accelerate innovation for reducing or eliminating the use of critical materials in EV batteries

RECOMMENDATION 1

Accelerate innovation in EV battery technology with lower material requirements. This report shows how innovation in EV batteries can have a significant influence on reducing potential supply bottlenecks. For instance, using LFP and LMFP batteries can effectively reduce the cobalt and nickel demand, while using sodium-ion batteries can also reduce the lithium demand. In the Increased Innovation scenario, characterised by these technologies, the demand for cobalt and nickel from EV batteries is, respectively, a third and half of the demand in the Technology Stagnation scenario. However, some technologies require efforts to overcome remaining technical challenges, establish new supply chains and achieve full commercialisation. To accelerate innovation, governments can identify relevant technologies and provide regulatory and financial support to boost research and development (R&D) and private sector investment. Governments can also facilitate collaboration between their agencies, academic institutions and private sector companies to promote knowledge sharing and joint R&D efforts in battery technology, and to facilitate the transition from research to large-scale production.

RECOMMENDATION 2

Monitor markets closely and frequently and increase industry engagement to stay abreast of the latest innovation trends and breakthroughs. EV battery technologies have evolved quite rapidly in recent years. This has led to significant shifts in critical material requirements. To address uncertainties arising from rapid demand shifts due to innovations in EV battery technologies, governments and critical material suppliers can establish systems to monitor these advancements closely, form strategic partnerships and actively engage with the EV battery sector. This proactive approach is needed for governments to respond effectively and in a timely manner to technological innovations by aligning regulatory frameworks, industry guidance and policy incentives with technological trends. Similarly, mining and processing companies, as well as battery manufacturers, should closely monitor technology trends to detect early signs of shifting material requirements, and allocate capital efficiently.

RECOMMENDATION 3

Accelerate the deployment of EV charging infrastructure to enable the adoption of smaller battery-sized EVs with lower material requirements. The size of EV batteries has a direct correlation with material demand. The estimated average passenger EV battery size in 2030 is about 57 kWh, although smaller battery sizes may be practical, for example, in cities. Governments can provide financial incentives and design regulations to build adequate EV charging infrastructure, a crucial enabler in reducing range anxiety and facilitating the adoption of vehicles with smaller battery sizes. Policy actions, such as tax credits or subsidies, can stimulate private investment in EV charging infrastructure, while mandatory inclusion of charging stations in parking lots, existing gas stations, and along high-density traffic roads and highways can ensure widespread accessibility.

Facilitate the rapid expansion of material mining and processing while adhering to the highest environmental, social and governance standards

RECOMMENDATION 4

Accelerate the development and expansion of mines by streamlining permitting processes. Road transport electrification will require ramping up mining production for all the materials discussed in this report by 2030, even if only the lowest demand projected in this study occurs. For instance, between 2023 and 2030, lithium would need to increase by up to approximately 160%; graphite supply would need to increase by about 60%; refined copper by about 13%; manganese by about 12% and nickel by about 10%. If demand exceeds these minimal estimates, then the actual increases in supply could be substantially higher. In light of this, government efforts can focus on streamlining regulatory and permitting processes, while maintaining the highest social and environmental protection standards. These efforts can include identifying and addressing inefficiencies in the permitting process, ensuring relevant agencies have sufficient capacity to process permits, making permitting requirements more transparent, digitalising the permitting process with a "one-stop-shop" platform and promoting co-ordination across different levels of government.

RECOMMENDATION 5

Support industry stakeholders to locate mining and processing activities in diverse geographies to make supply chains more resilient. Several critical materials used in EV batteries are mined in a handful of countries. For instance, in 2023, about 90% of lithium was mined in three countries, 80% of natural graphite was mined in two countries, nearly all synthetic graphite was produced in a single country and 60% of nickel was mined in two countries (QYResearch, 2023; USGS, 2024). Governments can address this significant vulnerability in the global supply chain by helping the industry and other countries increase diversification. Expanding the supply chain into reserve-rich countries but with low production levels can present opportunities for diversification. In the long run, increasing government exploration budgets and collaborating in geological surveys could help discover new reserves and attract investment in new locations. The production of processed materials is also highly concentrated. Supply chain diversification and support to economic growth, especially in developing countries, where much activity is focused on raw material export, necessitates promoting technology diffusion and investment in these regions. By progressing beyond merely increasing mined critical material exports, these countries can advance up the value chain. This progression would attract higher-margin activities, such as material refinement and EV equipment manufacturing, ultimately improving economic benefits and making supply chains more resilient (IRENA, 2023a).

RECOMMENDATION 6

Support the adoption of EV battery supply chains adhering to the principles of a sustainable, just and fair energy transition. The necessary expansion of mining operations should occur responsibly, upholding environmental integrity and the well-being of local communities. This includes addressing a range of environmental impacts, including but not limited to water pollution, greenhouse gas emissions, biodiversity loss, tailings disposal and waste management. Also crucial are engaging with local communities throughout the project cycle, ensuring fair labour conditions such as fair wages, stringent safety regulations and social protection for workers, and improved oversight and formalisation for artisanal and small-scale miners. Governance risks such as corruption, inadequate tax collection and revenue management also require action. International co-operation can help governments make their mandatory environmental, social and governance standards more robust and improve their capacity to enforce these laws effectively. The private sector can take additional voluntary measures and participate in collaborative initiatives such as the Extractive Industries Transparency Initiative, the Initiative for Responsible Mining Assurance, the UN Global Compact, and the International Council on Mining & Metals ten Sustainable Development Principles, among others.

RECOMMENDATION 7

Ensure the adequate supply of processed materials is not overlooked. This report highlights the potential supply and demand balance for selected EV battery raw materials by 2030. As described in the report, EV batteries have a limited influence on the supply and demand dynamics of phosphorus and manganese. This is because the majority of the demand for these materials stems from other uses (*e.g.* for phosphorous in agriculture and for manganese in the steel industry). However, derivative products of phosphorus and manganese, such as purified phosphoric acid and high-purity manganese sulphate, are essential for EV batteries and should not be overlooked. Given the necessity to expand and diversify the supply chain to meet the future demand for these processed products, governments can consider categorising phosphorous and manganese, or their derivatives essential for EVs, as critical materials. This classification could help prioritise investment and streamline permitting processes. Governments can also provide financial incentives to help private sector actors overcome high entry costs and increase funding for R&D to develop more sustainable processes.

Strengthen international co-operation to leverage each country's strengths, acknowledging that no single country possesses all the materials and knowledge required for the energy transition

RECOMMENDATION 8

Improve data transparency and availability in EV battery supply chains. This report highlights the uncertainties surrounding the demand and supply of critical materials. This includes demand-side uncertainties, for example, to what degree innovation may lead to shifts in material demand and supply-side uncertainties, including price volatility, geopolitical tensions, resource nationalism, export restrictions and regulatory changes. Informed decision making necessitates accessible and transparent data across the components of the EV battery supply chain. Relevant data categories include geological information, historical and real-time pricing, trade flows, supply-demand forecasts, among others. Governments, in collaboration with the private sector and international organisations, can improve the quality of data and make data more accessible by developing unified databases, promoting data sharing and establishing harmonised data standards.

RECOMMENDATION 9

Facilitate investment, knowledge sharing and capacity building to stimulate mining, processing and EV battery manufacturing in developing countries. Technologically advanced countries can facilitate the transfer of technology and expertise in critical material extraction, processing and utilisation. Partnering with nations with advanced manufacturing capabilities can facilitate knowledge exchange among developing countries and help them learn value-addition techniques for their raw materials. Such co-operation can help countries move up the value chain and make their critical material exports more profitable. Governments, supported by international organisations and industry stakeholders, can create exchange programmes and capacity-building initiatives for skill enhancement of geology, mining engineering, metallurgy and materials science professionals, in turn creating a capable workforce to advance the country's mining and materials sector. Such co-operation can also attract investment in infrastructure development, including transportation networks, energy facilities and processing plants. This infrastructure would not only benefit critical material extraction and processing but also support broader economic development and market expansion.

Maximise production from recyclable and scrap materials already in circulation and establish the groundwork for critical material recycling beyond 2030

RECOMMENDATION 10

Increase secondary production and consumption by utilising stocks of recyclable and scrap materials already in circulation. There already exists modest potential to reduce the demand for primary mined resources by increasing secondary supply. This is especially relevant for copper and nickel, whose use in large volumes across industries for many years has resulted in substantial scrap material available for secondary production. Scrap materials from EV battery manufacturing present further recycling potential for other materials in this decade. There are opportunities to boost secondary production by improving recycling technology and collection systems. Governments may create policies for promoting circularity to maximise these opportunities.

RECOMMENDATION 11

Prepare the groundwork to manage the large-scale EV battery recycling expected beyond 2030. Recycling may help mitigate supply chain bottlenecks to some extent by 2030. However, secondary production is not expected to become a major source of materials until the next decade, as technologies using materials in substantial quantities begin to reach their end of life. This is especially relevant for lithium and cobalt, whose use has grown significantly due to the large-scale EV adoption this decade, leading to higher volumes of recyclable materials. Innovation will lead to future batteries requiring fewer materials. Combined with advancements in recycling technologies, this means that when today's batteries are recycled, they will potentially yield more recoverable materials than are needed to produce new batteries.

Governments can proactively design policies to manage the large volumes of decommissioned EV batteries expected beyond 2030. These policies should prioritise developing circular economy regulations that promote EV battery recycling, ensure high material recovery rates and ensure batteries remain traceable throughout their lifespan. Governments can also invest in R&D to advance recycling processes and technologies, besides supporting recycling companies to invest in infrastructure and technology. Other key actions include clearly defining the roles and responsibilities of market participants; creating efficient collection systems to facilitate end-of-life battery stockpiling for recycling; and exploring opportunities in repurposing retired EV batteries to large-scale energy storage systems.

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ANNEX 1.

SUPPLY–DEMAND PROSPECTS PER MATERIAL

Annex 1.1. Lithium

Lithium, indispensable in all lithium-ion batteries, is primarily extracted from spodumene and brine ores before being processed into lithium carbonate (typically used for lithium iron phosphate [LFP] batteries) and lithium hydroxide (typically used for nickel manganese cobalt oxide [NMC] batteries) (Gielen and Lyons, 2022). Lithium production reached 0.96 Mt lithium carbonate equivalent (LCE) in 2023. Lithium reserves and resources, estimated at 150 Mt LCE and 485 Mt LCE, respectively, are ample to meet demand in the short to medium term (USGS, 2024). Beyond 2030, lithium recycling will be an important avenue for lithium supply; an estimated 0.4 Mt of LCE will be available for recycling annually by 2035 (BNEF, 2024c).

Lithium mining is highly concentrated; more than 90% was sourced from three countries (Australia, Chile and China) in 2023 (USGS, 2024). This concentration poses global supply vulnerabilities and risks (IRENA, 2023a). However, there are opportunities to diversify lithium mining and processing across multiple countries. There are already encouraging signs of diversification, with new players such as the Democratic Republic of Congo, Germany, Ghana and Portugal increasing their lithium exploration budgets (S&P Global, 2023).

Lithium demand will continue to be primarily driven by EV batteries, which are expected to represent approximately 82% of the total demand by 2030, marking a significant increase from a 62% share in 2022[10] (Figure A1.1). This percentage may, however, vary between 78% and 85% depending on the scenario and range of demand from other end uses. Demand from other sectors includes stationary energy storage, electronics and other industrial uses. Based on IRENA's analysis and forecasts from other organisations, the demand from other applications is estimated to be 0.43-0.60 Mt/year by 2030 (BNEF, 2024a; S&P Global, 2023).

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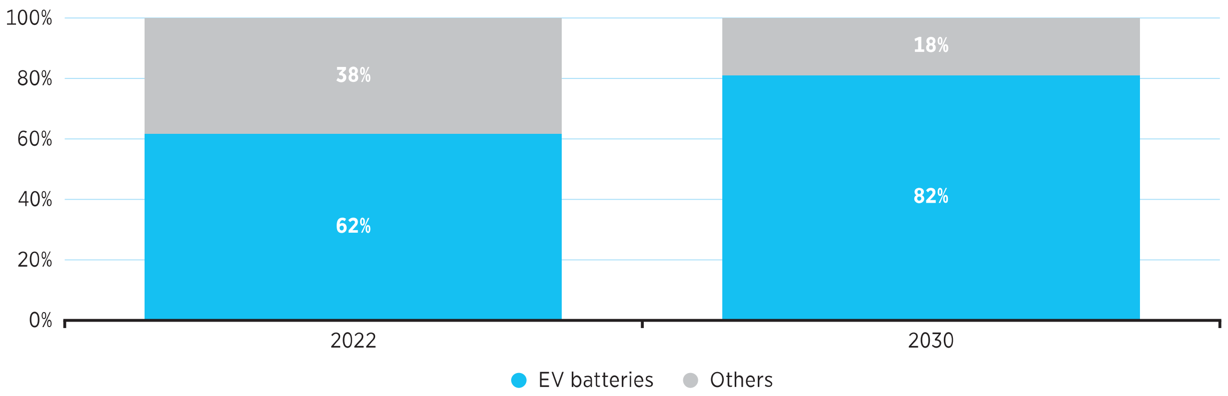
[10] *The demand for other applications reflects values from 2022, which are based on the latest data available.*

FIGURE A1.1 Lithium demand from EV batteries and other applications, 2022 and 2030

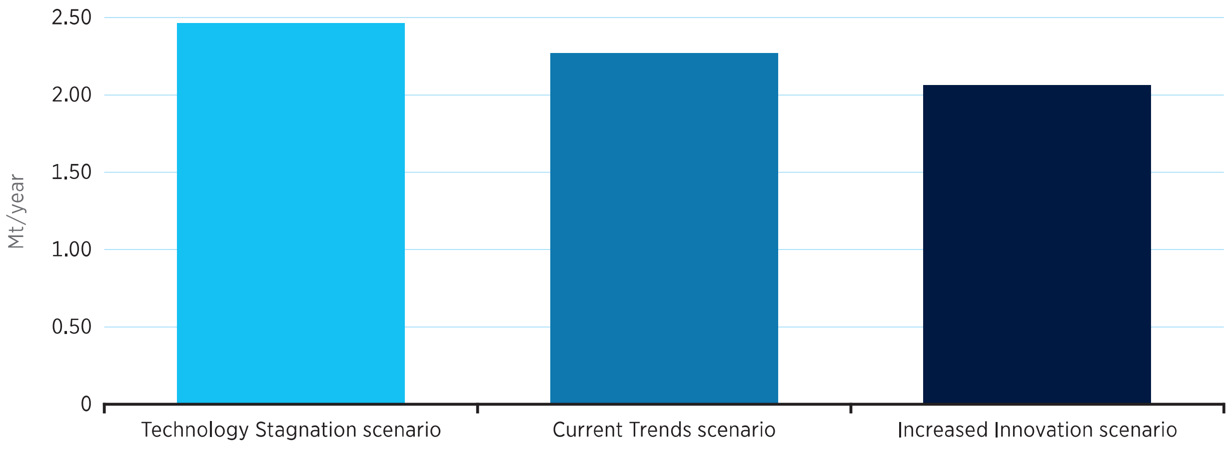


Source: Estimates for 2022 based on S&P Global (2023).

Notes: The figure illustrates the estimated share of demand from EV batteries and other applications by 2030 by providing an average estimate derived from IRENA's scenarios of EV battery demand and a range of estimates from other applications. EV = electric vehicle.

Lithium demand from EV batteries is anticipated to more than quadruple over 2023-2030 under the 1.5°C Scenario, with estimates ranging between 2.06 Mt/year and 2.47 Mt/year. The results from IRENA's three battery scenarios suggest demand for lithium remains largely unaffected by the evolution of the battery technology mix until 2030, given most technologies depend on lithium. Specifically, demand is estimated to be 2.47 Mt/year under the Technology Stagnation scenario, 2.27 Mt/year under the Current Trends scenario and 2.06 Mt/year under the Increased Innovation scenario (Figure A1.2). The cross-scenario variation in lithium demand primarily stems from the assumed degree of market penetration of sodium-ion batteries. While sodium-ion batteries may enter the market with substantial volumes in the second half of this decade, their impact on reducing lithium demand will likely be more significant after 2030.

FIGURE A1.2 Lithium demand from EV batteries by 2030 based on IRENA's battery chemistry scenarios

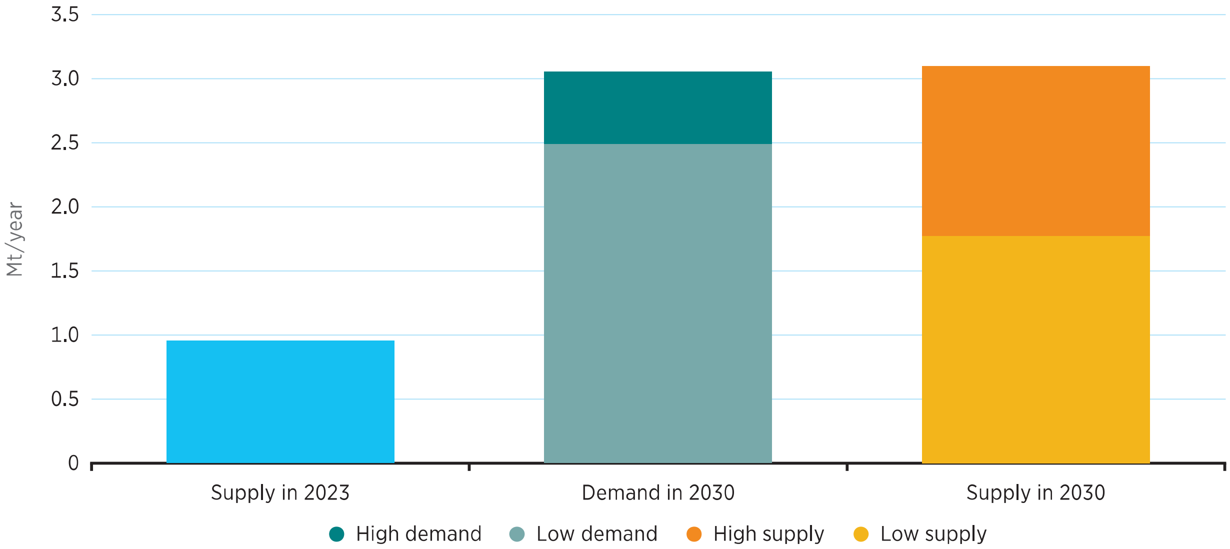


Notes: Values are expressed in million tonnes (Mt) of lithium carbonate equivalent (LCE). In the Technology Stagnation scenario, limited innovation is assumed and nickel-rich batteries are prioritised. In the Current Trends scenario, continuation of current innovation trends is considered and the dominance of LFP and LMFP batteries is explored. The Increased Innovation scenario is characterised by an increase in LFP and LMFP and a significant growth in sodium-ion technology.

The global total lithium demand – for EV batteries and other uses – is estimated to be 2.5-3.1 Mt/year by 2030, potentially tripling over the levels of 2023 (Figure A1.3). This demand estimation stems from IRENA's assessment of lithium demand from EV batteries (under the three scenarios in Figure A1.2) and a range of exogenous demand estimations from other applications.

On the supply side, an analysis of forecasts from other organisations suggests a lithium supply range between 1.8 Mt/year and 3.1 Mt/year by 2030 (Albemarle, 2023; BNEF, 2024a; ETC, 2023, 2023; Fitch Solutions, 2022; Jimenez *et al.*, 2022; S&P Global, 2023).

FIGURE A1.3 **Lithium supply and demand in 2023 and 2030**



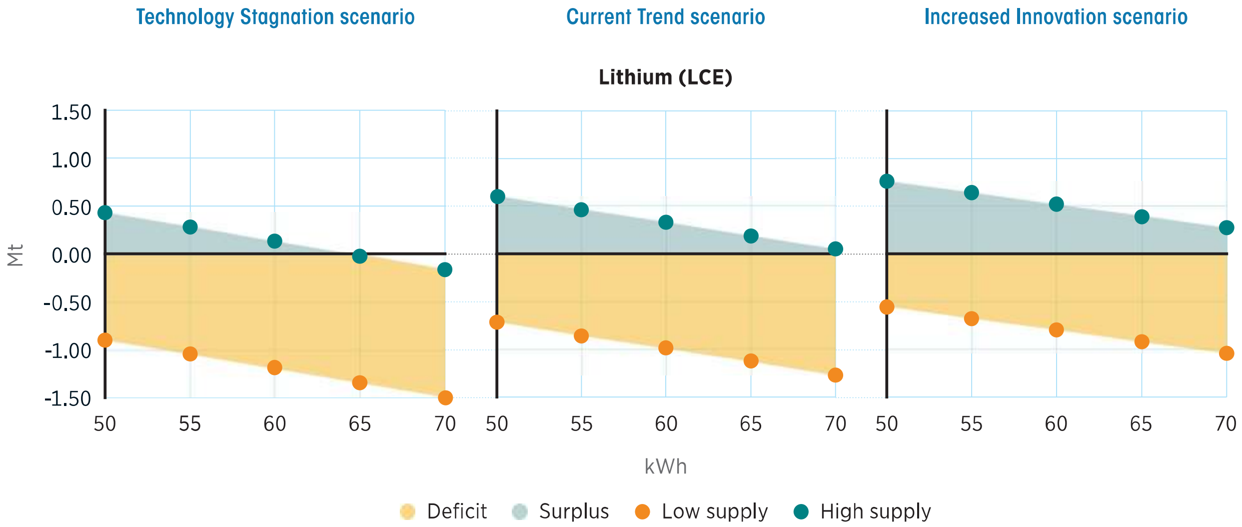
Sources: Supply-demand in 2023 based on USGS (2024); supply in 2030 based on Albemarle (2023), BNEF (2024a), ETC (2023, 2023), Fitch Solutions (2022), Jimenez *et al.* (2022) and S&P Global (2023).

Notes: Values are expressed in million tonnes of lithium carbon equivalent (LCE). Supply estimates for 2030 include announced, planned and potential supply. Mt = million tonnes.

Lithium deficits can be avoided if the supply pipeline materialises. Supply of lithium in processed form – lithium carbonate and lithium hydroxide – is also forecasted to proportionally meet the anticipated demand up to 2030 based on currently announced capacity (BNEF, 2024a). Beyond that, faster adoption of innovations, such as higher energy density batteries or the deployment of sodium-ion batteries, could further mitigate potential shortages by curbing demand. However, in a high-demand scenario, with supply falling in the lower range of estimates, significant shortfalls of up to 1.3 Mt/year could occur, representing about 40% of the demand in 2030.

Besides their chemistries, EV batteries' average size plays a crucial role in material demand, since battery size has a direct correlation with material demand. The sensitivity analysis in Figure A1.4 explores supply and demand for various battery sizes. It examines the impact of market shifts towards smaller as well as larger battery sizes. The yellow area of the graph delineates potential supply deficits, while the green area indicates potential supply surplus.

FIGURE A1.4 Lithium supply and demand balance in 2030 based on battery size sensitivity analysis



Notes: Values are expressed in million tonnes of lithium carbon equivalent (LCE). EV battery size sensitivity analyses for lithium supply balances are depicted separately for each scenario in the graph. A range of estimated supply is considered. For various battery sizes, orange dots represent market balance under low-supply conditions, while green dots denote market balance under high-supply scenarios. The yellow area indicates market shortfalls, while the green area highlights surpluses. kWh = kilowatt hour; LCE = lithium carbonate equivalent; Mt = million tonnes.

The sensitivity analysis shows that embracing innovative solutions (*e.g.* faster deployment of sodium-ion batteries) as well as avoiding further growth in average battery size minimises the risk of lithium supply deficits by 2030. However, supply imbalances are still possible in all scenarios if lithium supply stays in the lower range of projections. Addressing potential lithium deficits in the 2030 time frame will necessitate timely and effectively expanding the supply chain to meet the growing demand. Expanding the supply chain in nations where reserves are ample but production levels low, such as Brazil, Portugal and Zimbabwe, could facilitate supply chain diversification (USGS, 2024).

Annex 1.2. Cobalt

Cobalt has historically played a key role in lithium-ion batteries, contributing to an increase in energy density and thermal stability. However, innovations reducing cobalt use in NMC batteries, along with substitution with technologies such as LFP and LMFP, are leading to a rapid decrease in its criticality for the electrification of road transport.

The global production of refined cobalt reached 0.22 Mt in 2023 (Viernes, 2024; Cobalt Institute, 2021). An analysis, shown in Table 1, comparing cobalt resources in the Earth's crust with estimated demand indicates that there is sufficient cobalt to facilitate the energy transition. Global reserves stand at 11 Mt; global terrestrial resources are estimated at 25 Mt (USGS, 2024). It is important to note that cobalt is commonly mined as a by-product of copper and nickel mining, which limits its ability to adjust to market demand when compared with other materials.

Ongoing technological and regulatory advances in subsea mining could also soon open access to over 120 Mt of additional cobalt resources found in polymetallic nodules and crusts located in the seabed (USGS, 2024). However, a cautious approach is warranted due to uncertainties surrounding the environmental impact and regulatory frameworks. Further, cobalt is highly recyclable, and secondary production already constitutes nearly 15% of the overall supply (S&P Global, 2023). It is estimated that by 2030, 20% of the cobalt supply will come from recycled materials (Cobalt Institute, 2023).

Cobalt mining production is highly concentrated; more than 74% of mined production occurred in the Democratic Republic of Congo in 2023 (USGS, 2024). This concentration exposes cobalt to vulnerabilities, raising concerns regarding environmental, social and governance (ESG) factors, especially in artisanal and small-scale mining, which represents about 12% of cobalt mining activities (Cobalt Institute, 2022).

EV batteries are expected to account for about 46% of the total cobalt demand by 2030, compared with a 33% share in 2022[11] (Figure A1.5). The demand from other sectors includes batteries for electronics alongside diverse industrial applications. Based on IRENA's model and forecasts from other organisations, the estimated cobalt demand from these other applications is expected to be about 0.16 Mt/year by 2030.

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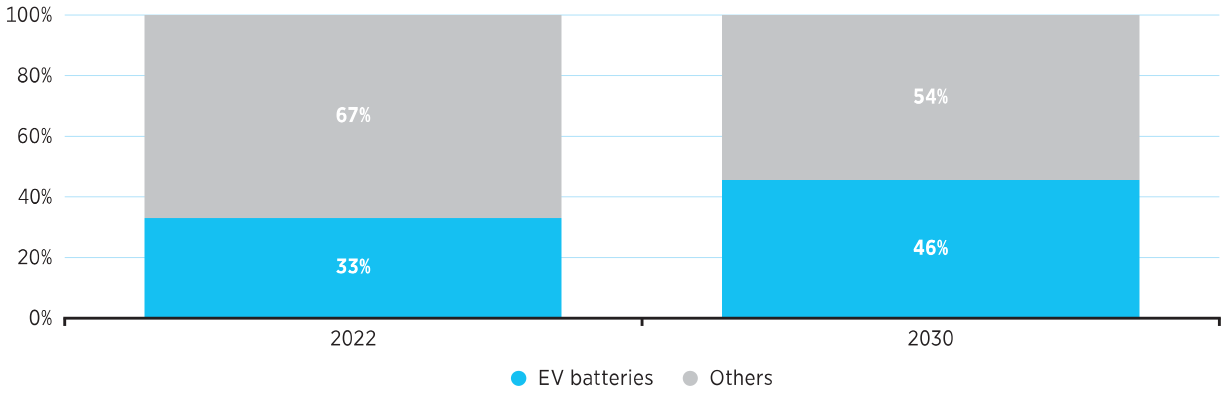
[11] *The demand for other applications reflects values from 2022, which are based on the latest data available.*

FIGURE A1.5 Cobalt demand from EV batteries and other applications, 2022 and 2030

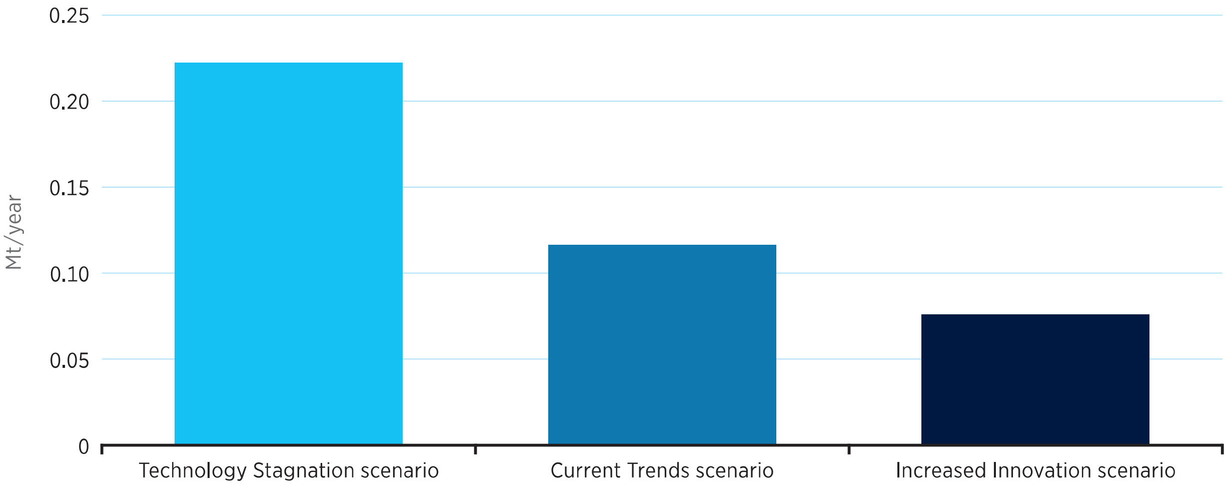


Source: Estimates for 2022 based on S&P Global (2023).

Notes: The figure illustrates the estimated share of demand from EV batteries and other applications by 2030 by providing an average estimate derived from IRENA's scenarios of EV battery demand and a range of estimates from other applications. EV = electric vehicle.

The future evolution of the battery technology mix would have a decisive impact on estimated cobalt demand from EV batteries. By 2030, cobalt demand from EV batteries is estimated to be 0.08-0.22 Mt/year (Figure A1.6). This suggests that the demand from EV batteries could grow significantly, ranging from 30% to 240%, compared with 2023, depending on the scenario. While a potential increase of more than three-fold in demand from EV batteries is suggested in the Technology Stagnation scenario, due to continued reliance on NMC, nickel manganese cobalt aluminium (NMCA) and nickel cobalt aluminium (NCA) batteries, demand in the Current Trends and Increased Innovation scenarios would be significantly lower due to the elimination of cobalt demand amid the use of LFP, LMFP, and sodium-ion technologies.

FIGURE A1.6 Cobalt demand from EV batteries by 2030 based on IRENA's battery chemistry scenarios

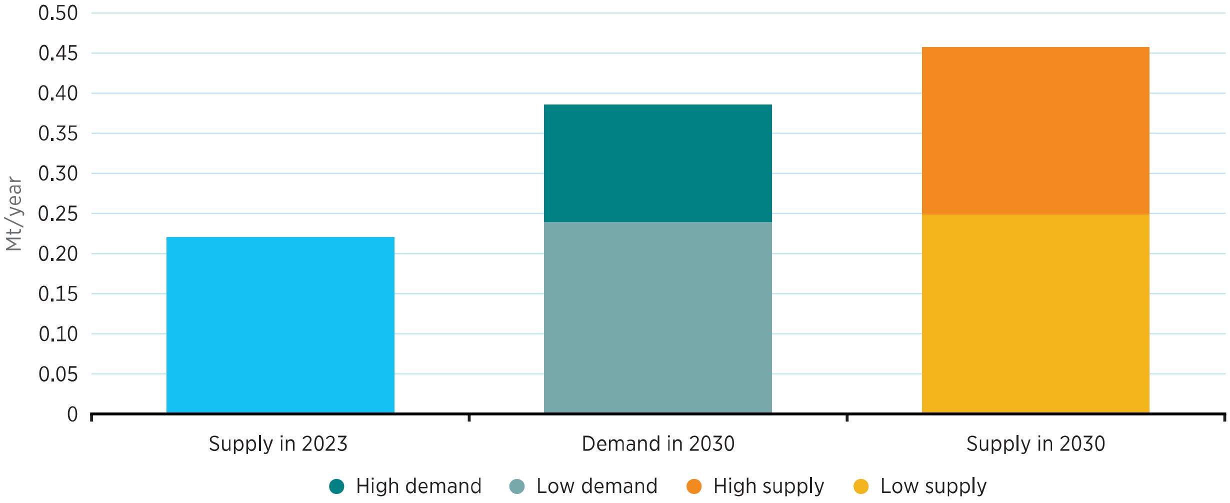


Notes: Values are expressed in million tonnes (Mt) of contained metal. In the Technology Stagnation scenario, limited innovation is assumed and nickel-rich batteries are prioritised. In the Current Trends scenario, the continuation of current innovation trends is considered and the dominance of LFP batteries is explored. The Increased Innovation scenario is characterised by an increase in LFP and a significant growth in sodium-ion technology.

Global total cobalt demand is estimated to be 0.24-0.39 Mt/year by 2030 (Figure A1.7). The results suggest that with innovation, the total cobalt demand could grow 10% between 2023 and 2030, to 0.24 Mt/year. Conversely, if current technological progress stalls, there could be a 75% increase in total cobalt demand, which could reach 0.39 Mt/year by 2030.

On the supply side, an analysis of forecasts from other organisations suggests a cobalt supply range of 0.25-0.46 Mt/year (BNEF, 2024a; Cobalt Blue Holdings, 2022; Darbar, 2022; ETC, 2023, 2023; Fu, 2020; Patterson *et al.*, 2023; S&P Global, 2023).

FIGURE A1.7 Cobalt supply and demand in 2023 and 2030



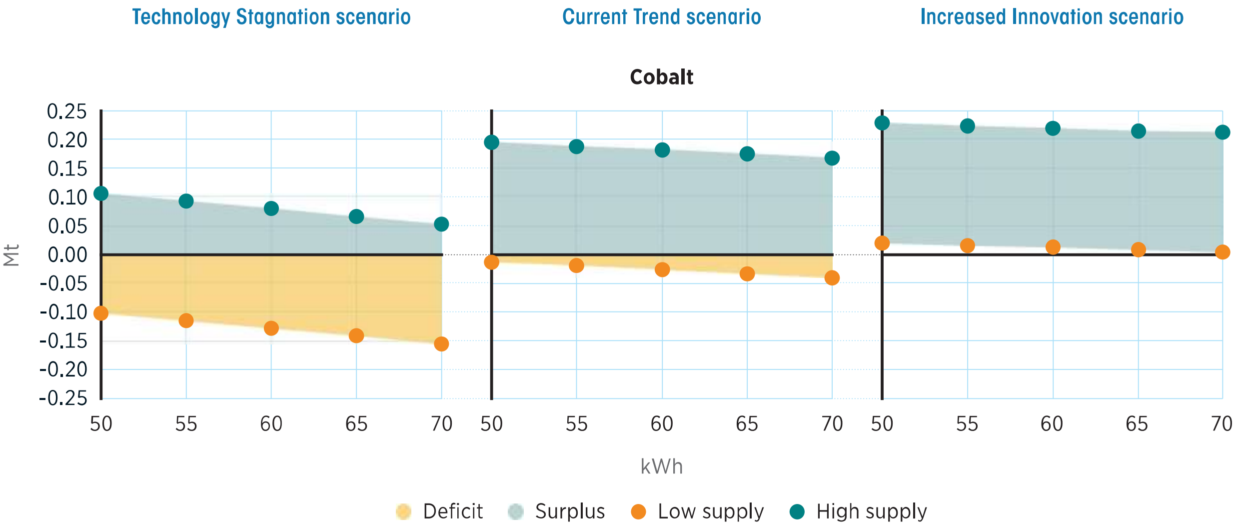
Sources: Supply-demand in 2023 based on USGS (2024); supply and demand in 2030 based on BNEF (2024a), Cobalt Blue Holdings (2022), Darbar (2022), ETC (2023, 2023), Fu (2020), Patterson *et al.* (2023) and S&P Global (2023).

Notes: Values are expressed in million tonnes (Mt) of contained metal. Supply estimates for 2030 include announced, planned and potential supply.

Cobalt supply deficits can be avoided if the current supply pipeline is developed. Additionally, there is potential to substitute cobalt demand from NMC, NMCA and NCA batteries with further adoption of LFP, and of the higher energy density LMFP battery types. Accelerating innovation in the energy density of these batteries would enable them to compete for the same market segments as nickel-rich battery types, further mitigating potential shortages by reducing demand. However, if the supply falls in the lower range of estimates and NMC, NMCA and NCA batteries remain prevalent, significant shortfalls of up to 0.14 Mt/year could occur, representing more than 35% of the demand in 2030.

Material demand from EV batteries is influenced by their average size and not just by their battery chemistries given that battery size directly correlates with material demand. The sensitivity analysis in Figure A1.8 explores supply and demand for various battery sizes. It examines the impact of market shifts towards smaller as well as larger battery sizes. The yellow area of the graph delineates potential supply deficits, while the green area indicates potential supply sufficiency.

FIGURE A1.8 Cobalt supply and demand balance in 2030 based on battery size sensitivity analysis



Notes: Values are expressed in million tonnes (Mt) of contained metal. EV battery size sensitivity analyses for cobalt supply balances are depicted separately for each scenario in the graph. A range of estimated supply is considered. For various battery sizes, orange dots represent market balance under low-supply conditions, while green dots denote market balance under high-supply scenarios. The yellow area indicates market shortfalls, while the green area highlights surpluses. kWh = kilowatt hour.

The sensitivity analysis shows that cobalt supply deficits can be avoided in all scenarios, regardless of the evolution of average battery size. It also shows that the risk of supply deficits is minimised through increased adoption of LFP, LMFP and sodium-ion batteries. However, under continued prevalence of NMC, NMCA and NCA batteries, some risk of supply bottlenecks remains if the higher end of the supply pipeline fails to materialise. Concerted efforts are needed to make cobalt supply chains more resilient; such efforts include adhering to the highest ESG standards and diversifying supply sources. Addressing the supply-demand gap in the short to medium term may require strategies such as reducing demand through innovation and securing further supply through recycling initiatives.

Annex 1.3. Graphite

Graphite is anticipated to remain the primary anode material for EV batteries towards 2030. This preference stems from graphite's inherent properties, which enable efficient charge retention and rapid charging. Whether sourced in its natural or synthetic form, graphite plays a crucial role in the composition of EV batteries; it constitutes the majority of the anode material in terms of mass.

Natural graphite

Among the different forms of natural graphite, including amorphous, crystalline and flake varieties, flake graphite is crucial for EV batteries, because it is suitable for producing battery-grade spherical graphite. In 2023, global natural graphite production was 1.6 Mt/year; the majority of the production originated from flake deposits (USGS, 2024). Natural graphite reserves and resources are ample. Estimated identified natural graphite reserves are at 280 Mt, while resources are at 800 Mt (USGS, 2024). However, global graphite production is heavily concentrated, with China representing nearly 75% of it in 2023, while Brazil, Madagascar and Mozambique collectively contribute another 20% (USGS, 2024). Given that production is highly concentrated, ongoing efforts aim to diversify mining and processing, including projects in countries such as Brazil, Canada, the United Republic of Tanzania, the United States, Sweden and Türkiye (Tsuji, 2022; Zhang, Liang and Dunn, 2023).

Synthetic graphite

Synthetic graphite, derived from fossil fuels such as petroleum coke, coal-tar pitch or oil, has been favoured by the EV battery industry due to its higher purity, faster charging speed and greater durability compared with natural graphite. However, natural graphite, known for its affordability and lower carbon intensity, presents a more sustainable alternative (Fastmarkets, 2023; Patterson *et al.*, 2023). In 2023, synthetic graphite production was estimated at about 2.4 Mt/year, reflecting a 7% increase over that in the previous year (QYResearch, 2023). China dominated the global synthetic graphite production, representing 35% of it, followed by Japan (21%), Europe (15%) and India (14%) (QYResearch, 2023).

The share of graphite demand from EV batteries is estimated to triple from 11% in 2022[13] to 31% by 2030 (Figure A1.9). However, this percentage may vary between 28% and 33% depending on the scenario and the range of demand from other end uses. Demand from other sectors includes that from the iron and steel industry, from aluminium production, from electronics manufacturing and from various industrial components. Based on IRENA's analysis and forecasts from other organisations, the demand from these other applications is estimated to be 4.5-5.2 Mt/year by 2030 (Black Rock Mining, 2023; QYResearch, 2023).

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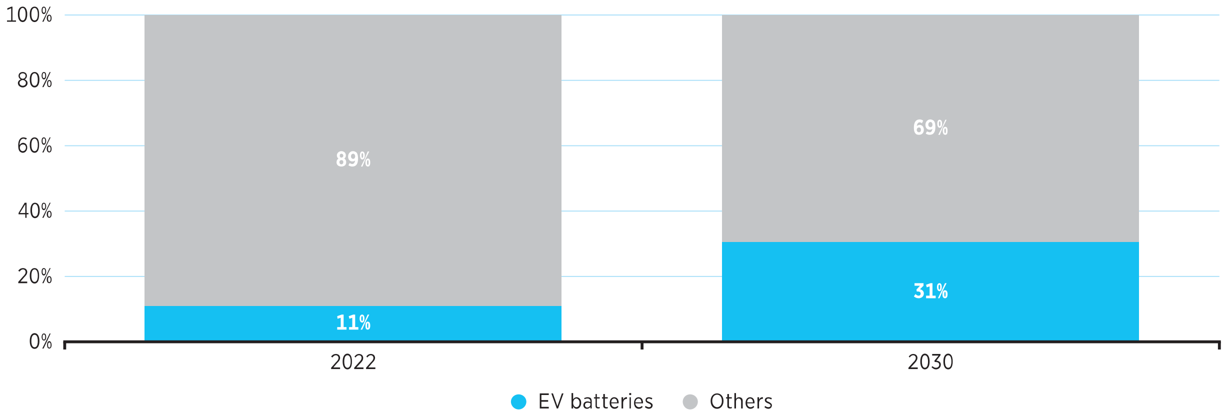
[12] *The demand from other applications reflects values from 2022, which are based on the latest data available.*

FIGURE A1.9 Graphite demand from EV batteries and other applications, 2022 and 2030

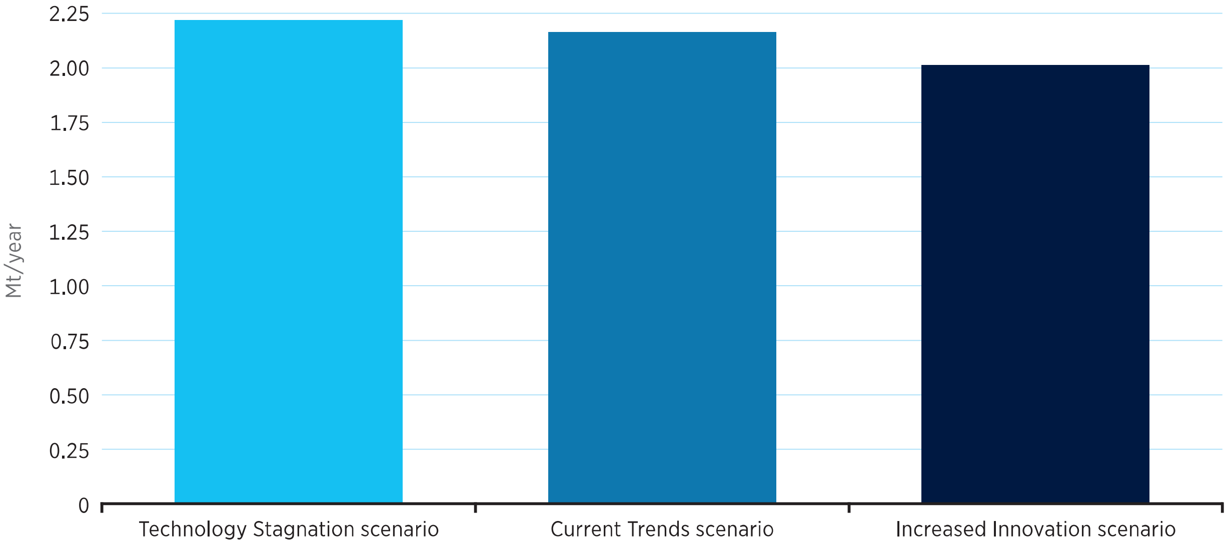


Sources: Estimates for 2022 based on NRCan (2021) and QYResearch (2023).

Notes: The figure illustrates the estimated share of demand from EV batteries and other applications by 2030 by providing an average estimate derived from IRENA's scenarios of EV battery demand and a range of estimates from other applications. The values include both natural and synthetic graphite demand. EV = electric vehicle.

Graphite demand from EV batteries could reach 2.0-2.2 Mt/year under the 1.5°C Scenario by 2030 (Figure A1.10). The results suggest that graphite demand remains relatively unaffected by the future evolution of the battery technology mix, since most technologies depend on graphite. The slight variation in graphite demand across scenarios primarily stems from the different shares of sodium-ion batteries, with the lowest graphite demand in the Increased Innovation scenario, in which the largest penetration of sodium-ion batteries is explored.

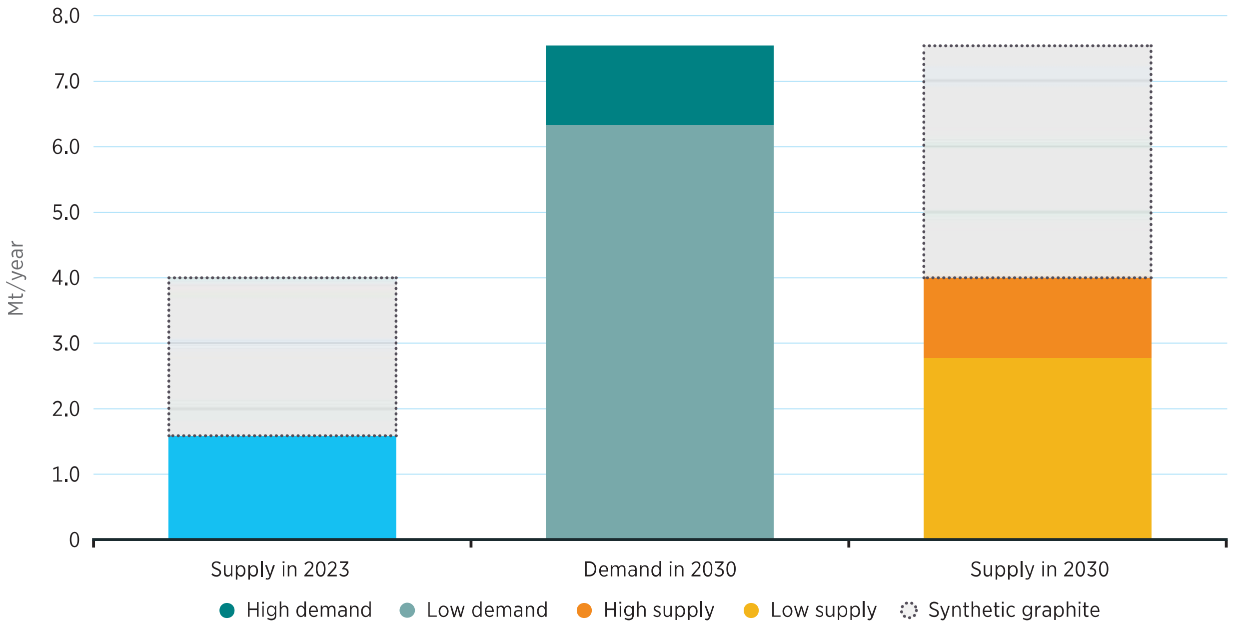
FIGURE A1.10 Graphite demand from EV batteries by 2030 based on IRENA's battery chemistry scenarios



Notes: Values are expressed in million tonnes (Mt) of contained metal. In the Technology Stagnation scenario, limited innovation is assumed and nickel-rich batteries are prioritised. In the Current Trends scenario, the continuation of current innovation trends is considered and the dominance of LFP batteries is explored. The Increased Innovation scenario is characterised by an increase in LFP and significant growth in sodium-ion technology. The values include both natural and synthetic graphite demand.

The global total graphite demand is estimated to be 6.5-7.4 Mt/year by 2030 (Figure A1.11). This demand estimation stems from IRENA's assessment of graphite demand from EV batteries (in the three scenarios in Figure A1.11) and a range of exogenous demand estimations from other applications. On the supply side, an analysis of forecasts from other organisations suggests a natural graphite supply range of 2.7-4.0 Mt/year by 2030 (Black Rock Mining, 2023; ETC, 2023; WSJ, 2023).

FIGURE A1.11 **Graphite supply and demand in 2023 and 2030**



Sources: Supply-demand in 2023 based on USGS (2024); supply in 2030 based on Black Rock Mining (2023), ETC (2023) and WSJ (2023).

Notes: Values are expressed in million tonnes (Mt) of contained metal. Graphite supply does not include synthetic graphite. Supply estimates for 2030 include announced, planned and potential supply.

Given the current supply estimates, natural graphite production, unless scaled up, will likely be insufficient to meet all expected graphite demand by 2030. Prioritising natural graphite remains crucial due to its lower emissions (QYResearch, 2023). However, should the supply of natural graphite fail to expand, bottlenecks can be avoided since synthetic graphite can bridge the gap; estimates project additional synthetic graphite supply of approximately 3.5 Mt/year by 2030 (QYResearch, 2023).

The ongoing transition to higher-silicon-content anodes and innovation in developing emerging anode technologies may alleviate pressure on graphite. Nevertheless, effectively addressing graphite deficits by 2030 requires scaling up the supply chain. Efforts should focus on expanding and diversifying natural graphite sources, while simultaneously striving to reduce emissions associated with synthetic graphite production. This can be achieved by improving energy efficiency, increasing the use of renewable energy sources and exploring alternative feedstocks like biomass and recycled plastics (Surovtseva *et al.*, 2022).

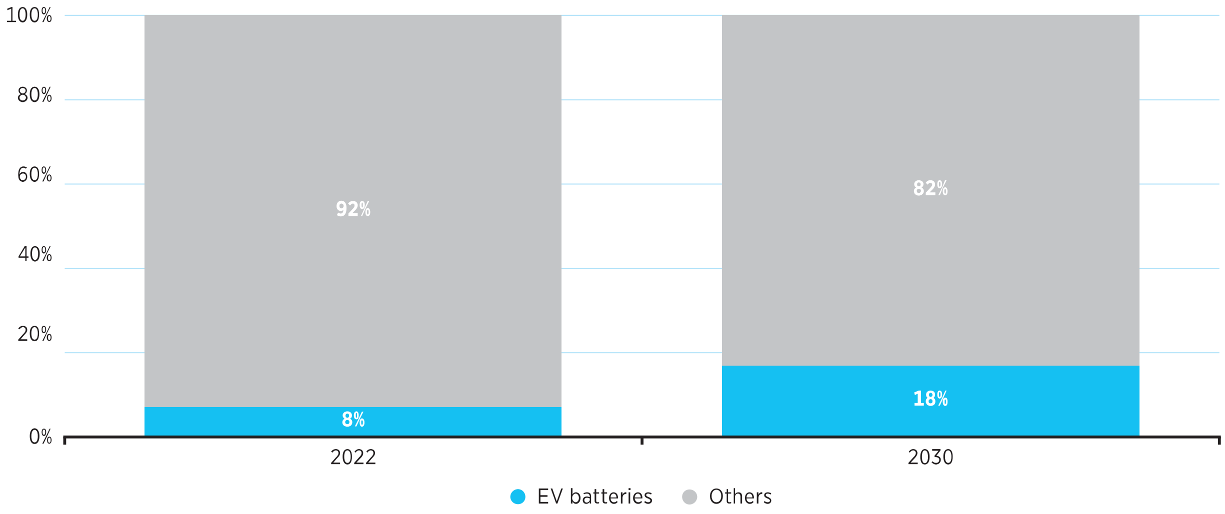
Annex 1.4. Nickel

Nickel is an important material in high-energy-performance EV batteries such as NMC, NMCA and NCA batteries. Nickel deposits are broadly of two ore types: sulphides and laterites. Sulphide is the primary source of high-grade nickel for EV batteries. Laterite ores can also be used for EV batteries, although upgrading low-grade laterite ores typically requires more energy (Transport & Environment, 2023). After mining, nickel is refined into products, which can be categorised as Class I (>99.8% purity), Class II (<99.8% purity) and nickel chemicals. EV batteries require Class I nickel, which represents only about 30% of all nickel produced (BNEF, 2023c).

There is sufficient nickel to facilitate the energy transition; nickel reserves and resources are estimated at more than 130 Mt and 350 Mt, respectively (USGS, 2024). Global nickel production reached 3.6 Mt/year in 2023 (USGS, 2024). Indonesia has positioned itself as the largest producer of nickel, both in terms of mining and processing. Nearly 60% of global nickel mining occurs in two countries: Indonesia and the Philippines.

The share of nickel demand from EV batteries is estimated to increase to about 18% by 2030, from approximately 8% in 2022[13] (Figure A1.12). However, this percentage may be 13%-24% depending on the scenario and the range of demand from other end uses. Other applications driving the nickel demand include stainless steel production, alloys, superalloys and consumer electronics. Based on IRENA's analysis and existing forecasts, the demand from these applications is estimated to be 3.4-3.6 Mt/year by 2030 (BNEF, 2024b; Canada Nickel, 2024).

FIGURE A1.12 Nickel demand from EV batteries and other applications, 2022 and 2030



Source: Estimates for 2022 based on S&P Global (2023).

Notes: The figure illustrates the estimated share of demand from EV batteries and other applications by 2030 by providing an average estimate derived from IRENA's scenarios of EV battery demand and a range of estimates from other applications. EV = electric vehicle.

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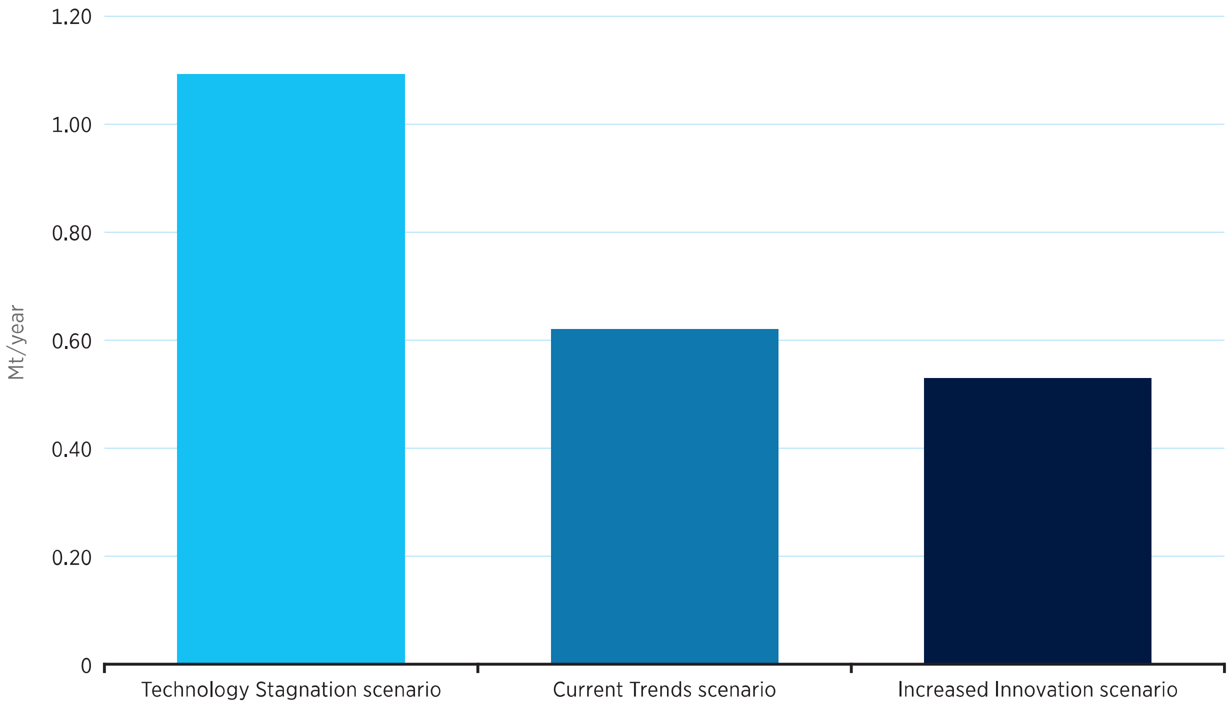
[13] *The demand from other applications reflects values from 2022, which are based on the latest data available.*

Based on IRENA's analysis, nickel demand from EV batteries could be 0.53-1.09 Mt/year by 2030, depending on the EV battery technology scenario (Figure A1.13). This means that nickel demand from EV batteries could potentially nearly double or quadruple over that in 2023, depending on the EV battery chemistry scenario. The results show that potential exists to halve the nickel demand from EV batteries through faster adoption of innovative battery technologies. This contrast stems from the reliance on nickel-rich batteries in the Technology Stagnation scenario, whereas in the Current Trends and Increased Innovation scenarios, a faster transition towards nickel-free technologies is explored, resulting in substantially lower nickel requirements.

FIGURE A1.13 **Nickel demand from EV batteries by 2030 based on IRENA's battery chemistry scenarios**

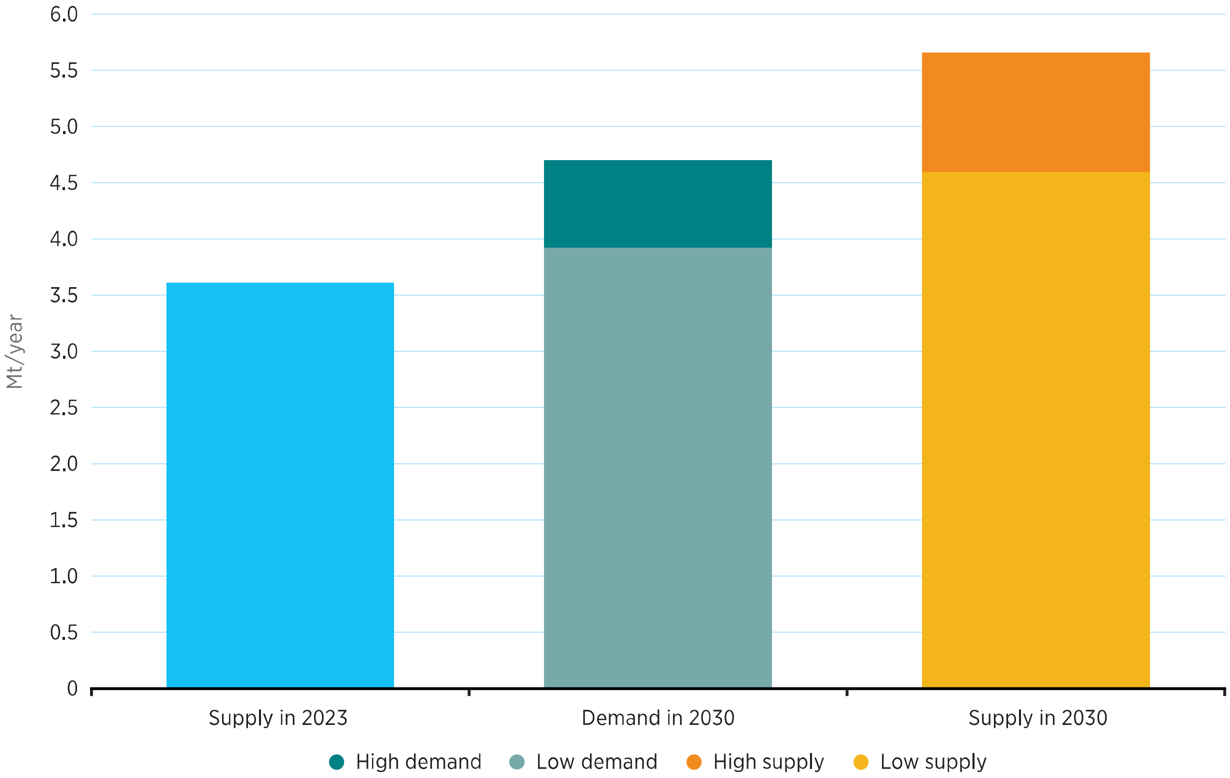


Notes: Values are expressed in million tonnes (Mt) of contained metal. In the Technology Stagnation scenario, limited innovation is assumed and nickel-rich batteries are prioritised. In the Current Trends scenario, the continuation of current innovation trends is considered and the dominance of LFP batteries is explored. The Increased Innovation scenario is characterised by an increase in LFP and significant growth in sodium-ion technology.

The total global nickel demand is estimated to be 3.9-4.7 Mt/year by 2030 (Figure A1.14). This demand estimation stems from IRENA's assessment of nickel demand from EV batteries (in the three scenarios in Figure A1.13) and a range of exogenous demand estimations from other applications.

On the supply side, an analysis of forecasts from other organisations suggests a nickel supply range of 4.6-5.6 Mt/year by 2030 (BNEF, 2024b; ETC, 2023, 2023; S&P Global, 2023).

FIGURE A1.14 Nickel supply and demand in 2023 and 2030



Sources: Supply-demand in 2023 based on USGS (2024); supply in 2030 based on BNEF (2024b), ETC (2023, 2023) and S&P Global (2023).

Notes: Values are expressed in million tonnes (Mt) of contained metal. Supply estimates for 2030 include announced, planned and potential supply.

The analysis of nickel supply and demand indicates a lower risk of supply deficits by 2030 relative to other critical materials if the current nickel supply pipeline materialises. Further, IRENA's battery chemistry scenarios show that transitioning away from NMC, NMCA and NCA batteries through the adoption of innovative battery technologies presents an opportunity to halve the nickel demand from EV batteries relative to a scenario in which nickel-based chemistries have a high share. Even if supply falls short of the upper estimates, only moderate shortfalls are estimated. However, it is important to note that while nickel supply shortages are not widely anticipated in this decade, deficits related to high-purity Class I nickel remain relevant for EV batteries. Projected supply for Class I nickel appears sufficient until 2028, but without additional project expansions, supply shortfalls may emerge by the decade's end (BNEF, 2023b).

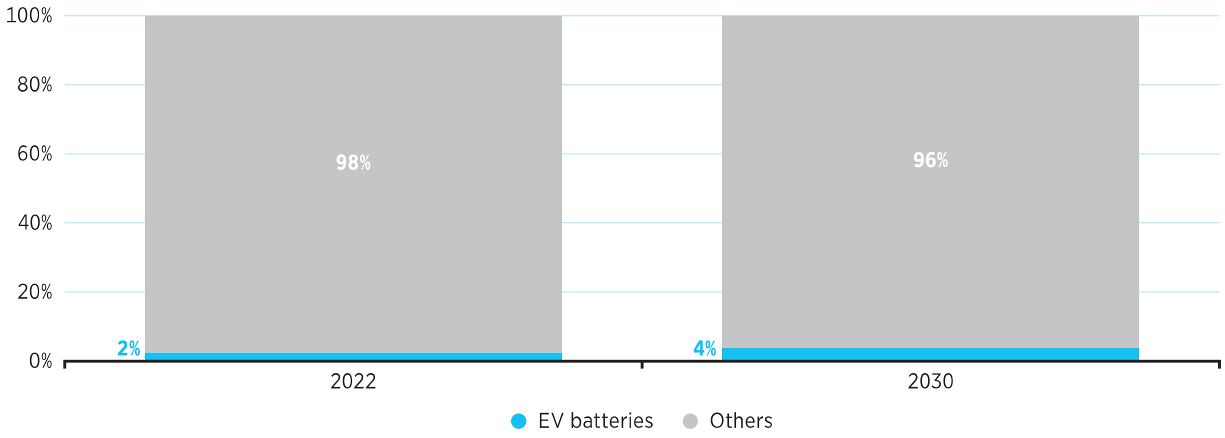
Annex 1.5. Copper

Copper is a key component within the wiring and casing structures of most EV batteries. For this purpose, mined copper needs to be refined to meet battery-grade standards. In 2023, refined copper production reached 27 Mt/year (USGS, 2024). Secondary sources, including recycled scrap, already contribute significantly to copper production; they represented nearly a fifth of the total production in 2022 (S&P Global IQ, 2022). In the broader context of supporting the energy transition, sufficient copper resources exist. With global copper reserves at 1000 Mt and global resources amounting to 3 500 Mt, there is confidence in meeting the estimated cumulative demand in the next decades (USGS, 2024).

While copper mining is less geographically concentrated than mining for other critical materials, more than half of its production happens in four countries: Chile, China, the Democratic Republic of Congo and Peru. On the other hand, 50% of copper refining was concentrated in just two countries, Chile and China, in 2023 (USGS, 2024).

The results from IRENA's model indicate a potential doubling of the share of copper demand from EV batteries, from 2% in 2022[14] to roughly 4% by 2030 (Figure A1.15). While this increase is notable, the bulk of the global demand for copper will continue to be driven by applications other than EV batteries. This includes building and construction; electronics; transportation equipment; and energy transition–related technologies such as electricity grids, renewable energy and EV charging infrastructure. The expected demand from these applications is 31-37 Mt/year by 2030 (IHS Markit, 2022;RFC Ambrian, 2022).

FIGURE A1.15 Refined copper demand from EV batteries and other applications, 2022 and 2030



Source: Estimates for 2022 based on S&P Global (2023).

Notes: The figure illustrates the estimated share of demand from EV batteries and other applications by 2030 by providing an average estimate derived from IRENA's scenarios of EV battery demand and a range of estimates from other applications. The estimated copper demand from EV batteries is based solely on the content within the battery pack, excluding other components, such as motor windings, wiring and electrical connections. EV = electric vehicle.

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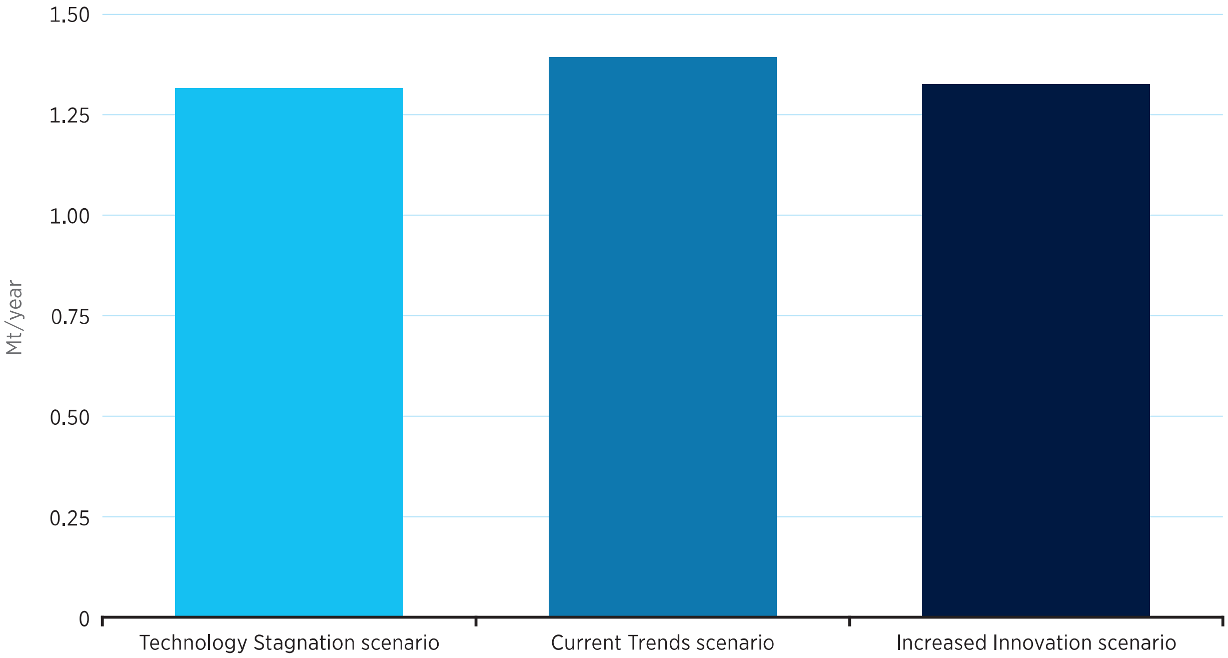
[14] *The demand from other applications reflects values from 2022, which are based on the latest data available.*

Refined copper demand from EV batteries could reach 1.32-1.39 Mt/year under the 1.5°C Scenario by 2030 (Figure A1.16). The higher demand in the Current Trends scenario is attributed to our assumption that LFP and LMFP batteries require slightly more copper than nickel-rich batteries. Copper demand is lower in the Increased Innovation scenario despite the prevalence of LFP and LMFP batteries. The lower demand is influenced by the absence of copper in sodium-ion batteries, where aluminium can replace copper in the anode, thus reducing the overall copper demand. Although EV batteries have varying copper requirements, the large scale of the overall copper market means future evolution of the market share of different battery technologies does not impact the market significantly.

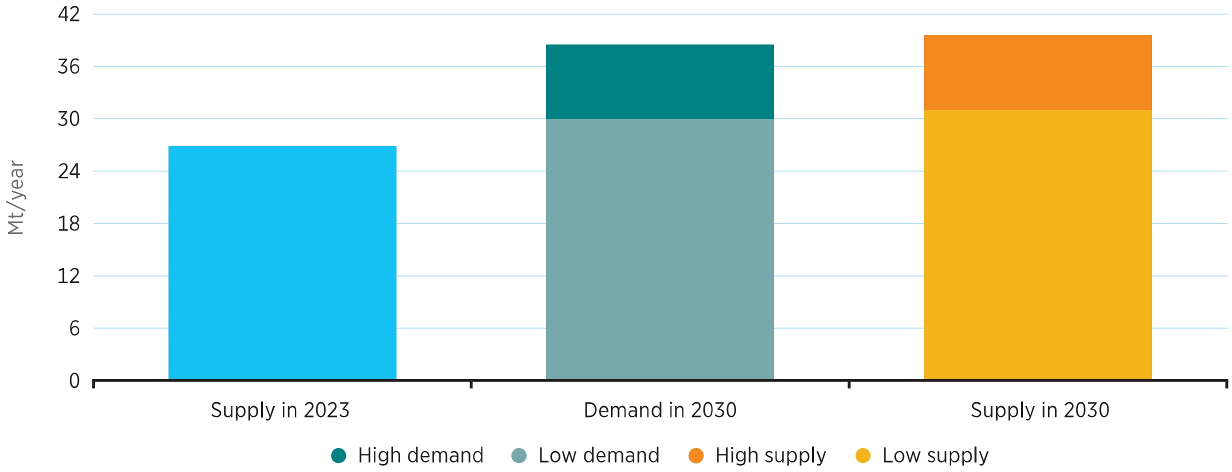
FIGURE A1.16 **Refined copper demand from EV batteries by 2030 based on IRENA's battery chemistry scenarios**



Notes: Values are expressed in million tonnes (Mt) of contained metal. In the Technology Stagnation scenario, limited innovation is assumed and nickel-rich batteries are prioritised. In the Current Trends scenario, the continuation of current innovation trends is considered and the dominance of LFP batteries is explored. The Increased Innovation scenario is characterised by an increase in LFP and significant growth in sodium-ion technology. The estimated copper demand from EV batteries is based solely on the content within the battery pack, excluding other components, such as motor windings, wiring and electrical connections.

By 2030, the global total refined copper demand is estimated to be 31-38 Mt/year (Figure A1.17). This wide range is primarily attributed to the range of demand estimates from other sectors, rather than EV batteries. Similarly, estimates for refined copper supply align within a comparable range of 31-39.5 Mt/year by 2030 (ETC, 2023, 2023; IHS Markit, 2022; RFC Ambrian, 2022; S&P Global IQ, 2022).

FIGURE A1.17 Refined copper supply and demand in 2023 and 2030



Sources: Supply-demand in 2023 based on USGS (2024), supply in 2030 is based on ETC (2023), IHS Markit (2022), RFC Ambrian (2022) and S&P Global IQ (2022).

Notes: Values are expressed in million tonnes (Mt) of contained metal. Supply estimates for 2030 include announced, planned and potential supply. The estimated copper demand from EV batteries is based solely on the content within the battery pack, excluding other components, such as motor windings, wiring and electrical connections.

Copper shortfalls by 2030 can be avoided if supply estimates materialise. Reaching this goal would require rapid development or expansion of copper mines, which typically entails a lead time of over 15 years. However, this timeline could be streamlined through supportive regulatory frameworks. Further, the expected growth in scrap supply, including both smelter and refinery feed and direct use of scrap, from 10 Mt/year in 2021 to nearly 12 Mt/year by 2030, underscores the sector's growth potential (Manalo, 2023; Soares, 2022).

However, fully realising the potential for increased copper scrap production beyond current forecasts hinges on addressing the sector's challenges, for example, scrap loss in landfills and the need for more equipment in scrap processing and separation. Overcoming the challenges requires significant investment in both capital and technology. Despite substantial progress, the sector's low profit margins in copper scrap collection and processing limit growth, underscoring the need for government policies promoting circularity (Manalo, 2023; Soares, 2022). Further, accelerating innovation efforts could potentially lead to additional demand reductions. While innovation in EV batteries may have a limited impact on the overall copper demand, other sectors hold promise. Notably, in electricity grids, aluminium is already extensively used in overhead transmission lines and, to a lesser extent, in subsea cables. Expanding this substitution to include underground transmission lines and increasing aluminium's use in subsea cables offers a viable and scalable alternative (IHS Markit, 2022; Gielen, 2021).

While there are growing concerns about potential supply constraints, it is feasible to avoid supply shortfalls by 2030. However, if supply falls at the lower range of estimates while demand reaches the upper range, significant supply deficits, amounting up to 7 Mt/year (or about a fifth of potential demand), could arise by 2030.

Annex 1.6. Phosphorous

Phosphorous is indispensable in the agriculture sector for fertilisers and is also a key material in LFP and LMFP batteries. Phosphorous production, which primarily originates from phosphate rock, was estimated to have been approximately 22.5 Mt/year[15] in 2023. Global phosphate rock reserves are vast and estimated at 72 000 Mt, equivalent to over 7 000 Mt of phosphorous (USGS, 2024). Identified global resources of phosphate rock exceed 300 000 Mt. Despite the high availability of phosphate rock, its production is highly concentrated – about 65% in three countries, China (40%), Morocco (16%) and the United States (9%) (USGS, 2024).

While phosphate rock is in abundance, not all of it is suitable for producing purified phosphoric acid (PPA), which is essential for EV batteries. The specific type of phosphate rock essential for PPA production, known as igneous feedstock, has limited availability; it constitutes only about 5% of the world's phosphate rock (Hotter, 2023). Of this 5%, only the purest 1%, referred to as igneous anorthosite, can be used to produce significant quantities of battery-grade PPA (Hotter, 2023).

The search for viable sources of igneous rock, containing the appropriate feedstock for EV batteries, has led to exploration expanding in regions such as Brazil, Canada, Finland, the Russian Federation and South Africa. However, there are concerns about the availability of projects to meet the anticipated surge in demand for PPA. The lack of sufficient capacity and of ongoing projects could hinder ensuring a stable supply of PPA for the growing demand in the EV battery industry (Hotter, 2023).

Even under high LFP and LMFP deployment, the demand for phosphorus from EV batteries is estimated to account for only about 3% of the total demand by 2030 (Figure A1.18). While this is a substantial increase from about 1% in 2022,[16] the majority of the phosphorous demand stems from other uses, such as fertiliser and animal supplement feeds. Based on IRENA's analysis, the demand from non-EV battery applications is estimated to be 27.6-28.3 Mt/year by 2030.

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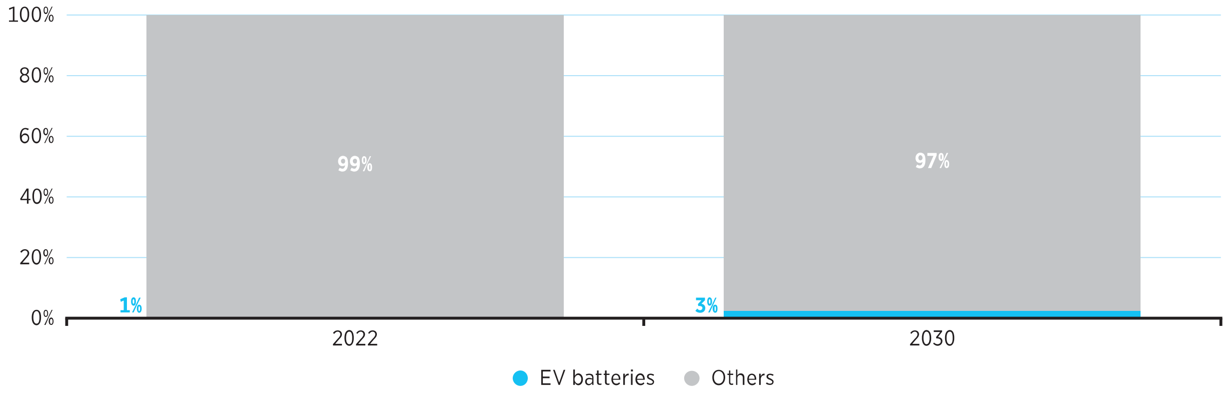
[15] *Phosphorous supply is sourced from global phosphate rock production; phosphorus pentoxide has an assumed 25% share in phosphate rock. A 44% share of phosphorus in phosphorus pentoxide is considered.*

[16] *The demand from other applications reflects values from 2022, which are based on the latest data available.*

FIGURE A1.18 Phosphorous demand from EV batteries and other applications, 2022 and 2030

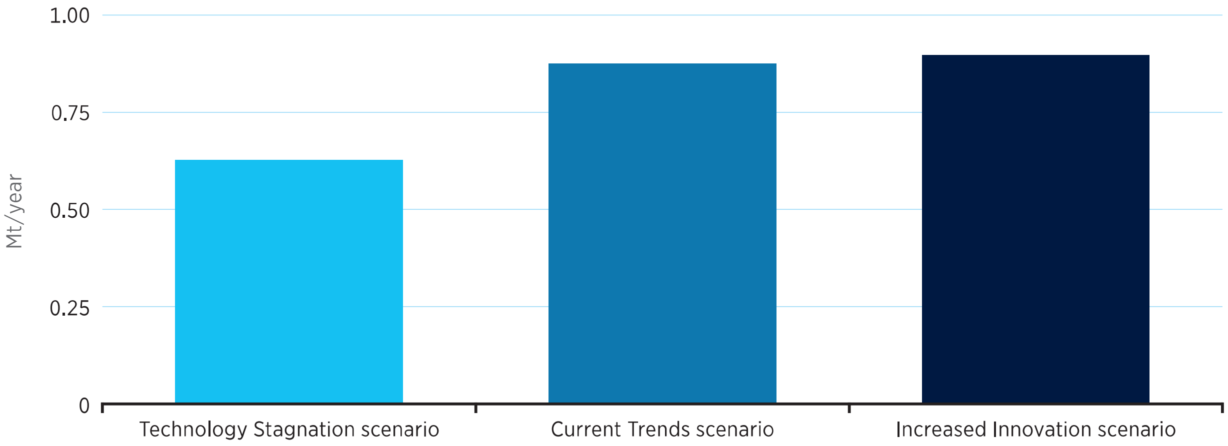


Sources: Estimates for 2022 based on Bownlie *et al.* (2022) and USGS (2024).

Notes: The figure illustrates the estimated share of demand from EV batteries and other applications by 2030 by providing an average estimate derived from IRENA's scenarios of EV battery demand and a range of estimates from other applications. EV = electric vehicle.

The demand for phosphorus in EV batteries could reach 0.63-0.90 Mt/year under the 1.5°C Scenario by 2030 (Figure A1.19). The demand would be 0.63 Mt/year in the Technology Stagnation scenario, 0.88 Mt/year in the Current Trends scenario, and 0.90 Mt/year in the Increased Innovation scenario. Notably, demand is markedly higher in the Current Trends and Increased Innovation scenarios, where LFP batteries hold a larger market share, compared with the Technology Stagnation scenario. However, it is important to contextualise this demand within the broader phosphorus market. Despite the variations across scenarios, the estimated demand from EV batteries remains relatively modest, representing only about 3% of the estimated market in 2030. Therefore, while the demand for phosphorus fluctuates depending on the scenario, the impact from EV batteries is expected to remain minimal.

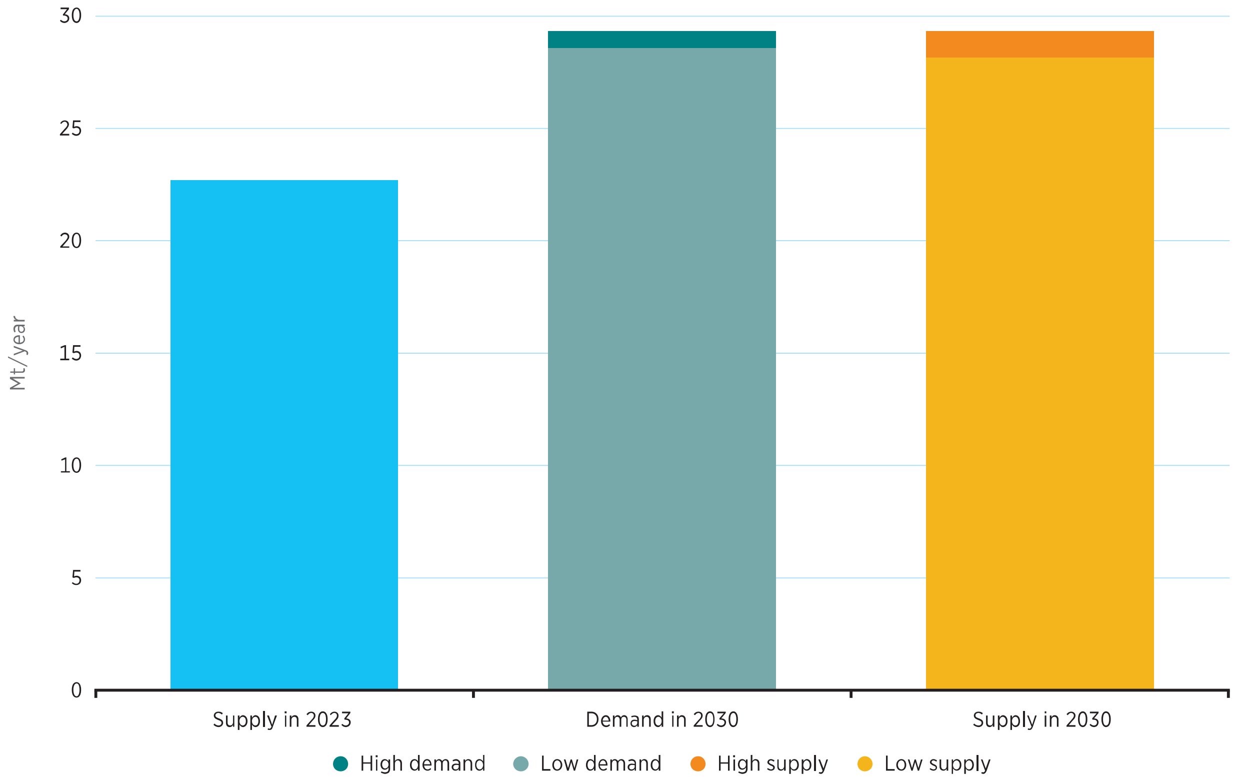
FIGURE A1.19 Phosphorous demand from EV batteries by 2030 based on IRENA's battery chemistry scenarios



Notes: Values are expressed in million tonnes (Mt) of contained elemental phosphorous. In the Technology Stagnation scenario, limited innovation is assumed and nickel-rich batteries are prioritised. In the Current Trends scenario, the continuation of current innovation trends is considered and the dominance of LFP batteries is explored. The Increased Innovation scenario is characterised by an increase in LFP and significant growth in sodium-ion technology.

The total global phosphorus demand is estimated to be 28.2-29.2 Mt/year by 2030, reflecting a 25%-30% increase over the levels in 2023 (Figure A1.20). This demand range stems from the three EV battery chemistry scenarios and the demand from other uses. Consistent with these demand estimates, phosphorus supply estimates range from 28.0 Mt/year to 29.2 Mt/year by 2030. The analysis has been conducted considering the estimated growth of fertiliser demand and various underlying assumptions, for example, a range of phosphate rock ore grades.

FIGURE A1.20 **Phosphorous supply and demand in 2023 and 2030**



Sources: Supply in 2023 based on Bownlie *et al.* (2022) and USGS (2024).

Notes: Values are expressed in million tonnes (Mt) of contained elemental phosphorous. In the Technology Stagnation scenario, limited innovation is assumed and nickel-rich batteries are prioritised. In the Current Trends scenario, the continuation of current innovation trends is considered and the dominance of LFP and LMFP batteries is explored. The Increased Innovation scenario is characterised by an increase in LFP and LMFP and significant growth in sodium-ion technology.

Phosphorous supply and demand estimates for 2030 appear relatively balanced. Based on this analysis, a phosphorous supply shortfall could be avoided if the current supply estimates materialise. Efforts to utilise phosphorus resources more efficiently, particularly in applications playing a significant role in phosphorus demand (*e.g.* agriculture), could further mitigate potential supply shortfalls. While phosphorus demand from EV batteries is not expected to be a significant driver, addressing issues surrounding battery-grade PPA supply emerges as the most pressing concern, requiring concerted actions to rapidly expand PPA supply chains.

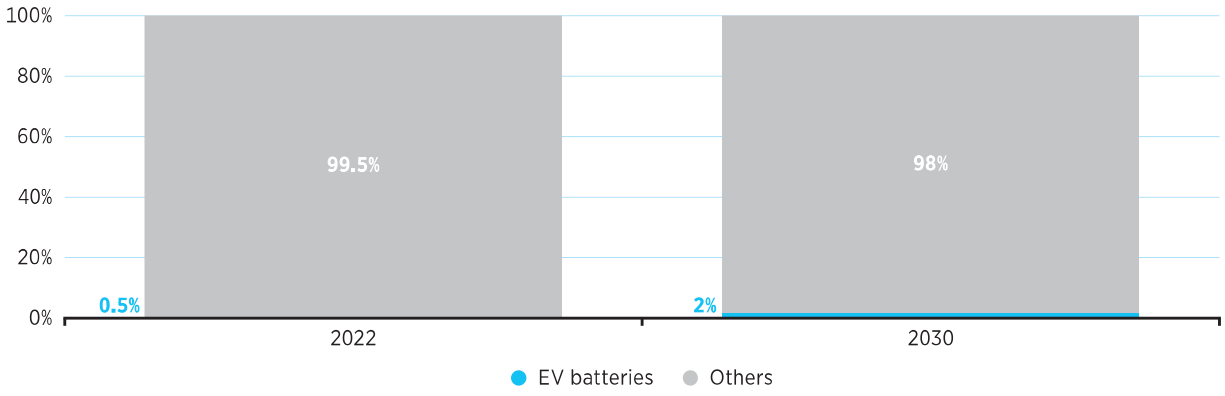
Annex 1.7. Manganese

Manganese is used in several EV battery technologies; including NMC, NMCA, LMFP, LMO and certain types of sodium-ion batteries. Mined manganese ore is refined to produce battery-grade high-purity manganese. Global manganese production was estimated to be 20 Mt/year in 2023 – mostly unchanged from 2022 (USGS, 2024). Manganese is an abundant material. Manganese reserves are estimated at 1900 Mt, along with an additional 450 Mt in deep-sea deposits (USGS, 2024). Manganese mining is notably concentrated; with nearly 75% of its production is in Australia, Gabon and South Africa. The vulnerabilities of such concentration were already felt in 2023, when political instability and weather-related issues affected the supply chain (USGS, 2024).

While manganese itself is not scarce, battery-grade high-purity manganese has associated supply risks. The forecasted demand for processed high-purity manganese for 2030 is more than three times the announced supply production (BNEF, 2024a). Further, the production landscape is highly centralised, with China representing 96% of global output. While Australia, Canada and Chile have new projects for high-purity manganese, the market is in its early stages. New entrants face significant barriers due to the costly and complex processing, and some existing refineries rely on environmentally unfriendly chemical processes, conflicting with carmakers' ESG priorities (Silva, 2023). In Europe, the first high-purity manganese processing facility utilising tailings recovery is being developed in Czech Republic (Lui, 2022).

Like other materials not primarily driven by EV batteries, such as copper and phosphorous, the demand for manganese from EV batteries is expected to play a secondary role in shaping the dynamics of this material's supply and demand, accounting only for about 2% of the total demand for manganese (Figure A1.21). The main applications of manganese are primarily in steelmaking, as well as in aluminium alloys and other industrial uses. Based on IRENA's analysis and forecasts from other organisations, the manganese demand from these applications is estimated to be 22.2-25.5 Mt/year by 2030 (Jupiter Mines, 2023; World Steel, 2023).

FIGURE A1.21 **Manganese demand from EV batteries and other applications, 2022 and 2030**



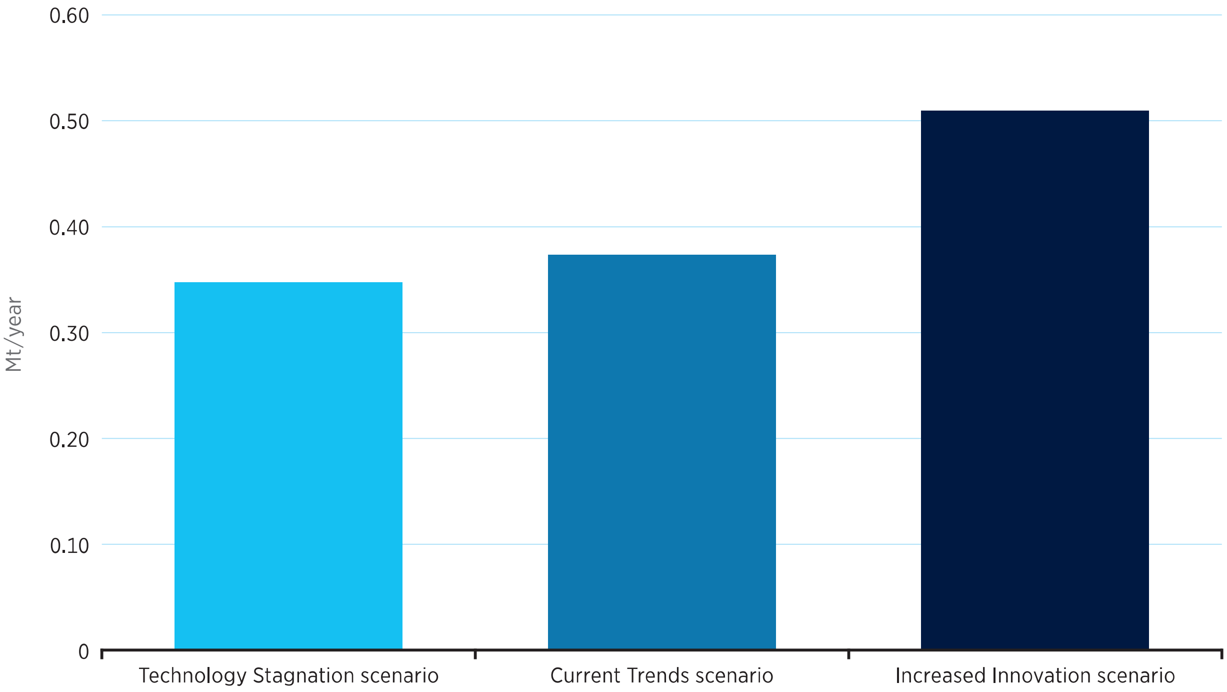
Source: Estimates for 2022 based on SMM (2022).

Notes: The figure illustrates the estimated share of demand from EV batteries and other applications by 2030 by providing an average estimate derived from IRENA's scenarios of EV battery demand and a range of estimates from other applications. The demand from other applications reflects values from 2022, which are based on the latest data available. EV = electric vehicle.

The manganese demand from EV batteries could reach 0.35-0.51 Mt/year under the 1.5°C Scenario by 2030 (Figure A1.22). The results show that demand is estimated to be 0.35 Mt/year in the Technology Stagnation scenario, 0.37 Mt/year in the Current Trends scenario and 0.51 Mt/year in the Increased Innovation scenario.

The diverse manganese requirements across different EV battery technologies lead to variation in demand across scenarios. Manganese demand is comparable in the Technology Stagnation and Current Trends scenarios, although the overall manganese content is slightly higher in the Current Trends scenario because lower-manganese-content NMC batteries are increasingly being replaced by higher-manganese-content LMFP and sodium-ion batteries. Manganese demand is highest in the Increased Innovation scenario, which builds on the trends from the Technology Stagnation to Current Trends scenarios but includes an even greater adoption of sodium-ion batteries, driving up manganese demand further. Specifically, the increased use of layered metal oxide sodium-ion batteries, which our analyses assume contains moderate amounts of manganese, contributes to this demand. It is important to note that these metal oxides have multiple configurations, and not all include manganese. Additionally, since sodium-ion technology is evolving rapidly, the material requirements for these batteries are expected to decrease. Other sodium-ion technologies, such as Prussian blue analogues and polyanionic types, which do not rely on manganese, might also become more prominent than currently anticipated.

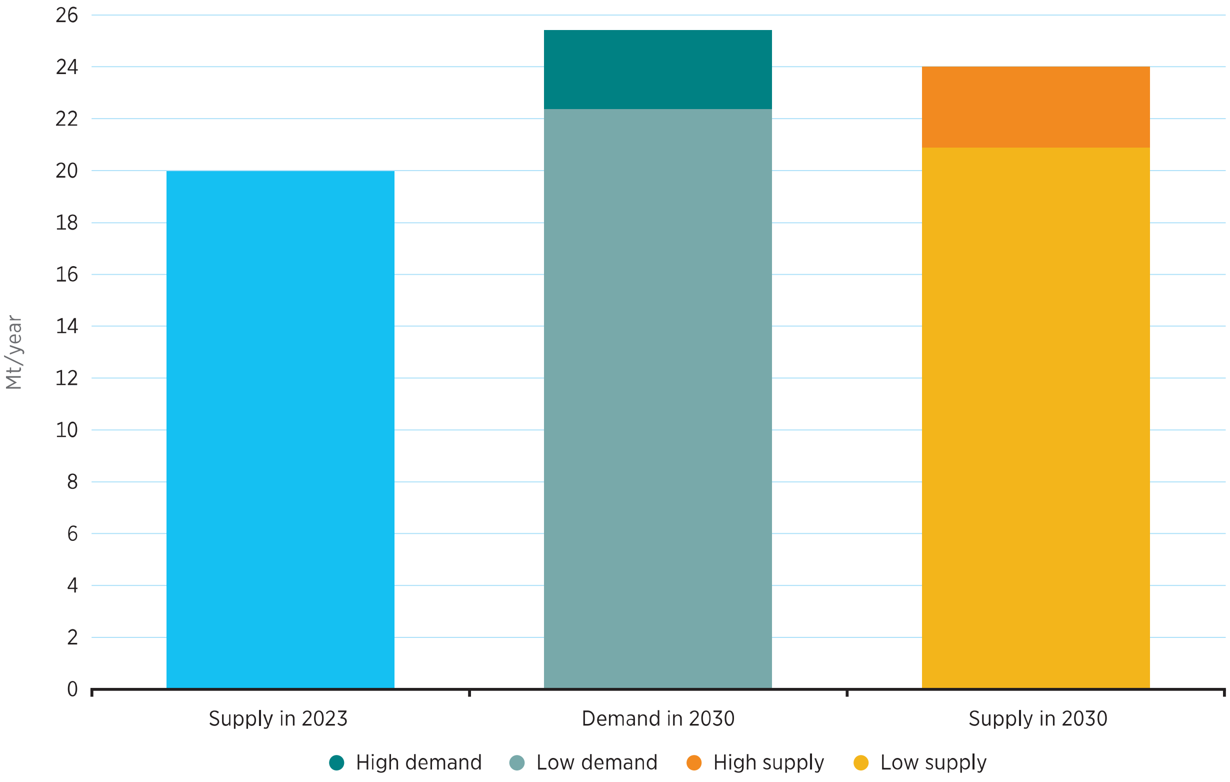
FIGURE A1.22 **Manganese demand from EV batteries by 2030 based on IRENA's battery chemistry scenarios**



Notes: Values are expressed in million tonnes (Mt) of contained metal. In the Technology Stagnation scenario, limited innovation is assumed and nickel-rich batteries are prioritised. In the Current Trends scenario, the continuation of current innovation trends is considered and the dominance of LFP/LMFP batteries is explored. The Increased Innovation scenario is characterised by an increase in LFP/LMFP and significant growth in sodium-ion technology.

Total global manganese demand is estimated to be 22.5-26.0 Mt/year by 2030, a significant increase from 20 Mt/year in 2023 (Figure A1.23). This demand range stems from the three EV battery chemistry scenarios and is primarily influenced by the demand range from other applications. In contrast, an analysis of forecasts from other organisations suggests a manganese supply estimate range of 21-24 Mt/year by 2030 (Jupiter Mines, 2023; McKinsey, 2022).

FIGURE A1.23 Manganese supply and demand in 2023 and 2030



Sources: Supply-demand in 2023 based on USGS (2024); supply in 2030 based on Jupiter Mines (2023) and McKinsey (2022).

Notes: Values are expressed in million tonnes of contained metal. Supply estimates for 2030 include announced, planned and potential supply. Mt = million tonnes.

There is a potential risk of manganese supply shortfalls by 2030. However, these risks could be managed if current supply estimates materialise, and demand remains within the lower limit. Achieving this requires increasing supply, and ongoing innovation and demand reduction efforts would further alleviate supply pressures. EV batteries are expected to account for only about 1.3%-2.6% of total manganese demand. They would thus have a minor impact on manganese supply and demand dynamics relative to steelmaking, the primary driver of demand. When considering manganese for EV batteries, concern is not primarily about the availability of raw manganese ore, but the unmatched demand for high-purity manganese. Therefore, mass deployment of EVs by 2030 will require ramping up the production of high-purity manganese.

ANNEX 2.

KEY ASSUMPTIONS

TABLE A2.1 Global average EV battery size per vehicle segment, 2022 and 2030

[kWh/vehicle]	2022	2030
BEV car/SUV/van	61	63
PHEV car/SUV/van	14	14
EV car/SUV/van	48	57
Small trucks	100	100
Motorcycles	0.50	2.25
Buses	160	185
Large trucks	680	390

Based on: Argonne National Laboratory (2022), BNEF (2024a) and ICCT (2021).

Notes: The values for the EV car/SUV/van category are based on a weighted average of the shares of BEVs and PHEVs in 2022 and the estimated share for the EV car/SUV/van category in 2030. Small trucks refers to light-duty commercial vehicles, while large trucks refers to medium and heavy commercial vehicles. BEV = battery electric vehicle; kWh = kilowatt hour; PHEV = plug-in hybrid electric vehicle; SUV = sports utility vehicle.

TABLE A2.2 EV battery chemistry mix for cars/SUVs/vans by scenario, 2030

[% of vehicle sales]	Technology Stagnation scenario	Current Trends scenario	Increased Innovation scenario
LFP	35%	49%	49%
LMFP	15%	21%	21%
NCA	8%	5%	3%
NMC	40%	20%	12%
Na-ion	2%	5%	15%

Notes: LFP = lithium iron phosphate; LMFP = lithium manganese iron phosphate; Na = sodium; NCA = nickel cobalt aluminium oxide; NMC = nickel manganese cobalt oxide.

TABLE A2.3 EV battery chemistry mix for motorcycles by scenario, 2030

[% of vehicle sales]	Technology Stagnation scenario	Current Trends scenario	Increased Innovation scenario
LFP	24%	43%	43%
LMFP	16%	27%	27%
NCA	10%	5%	0%
NMCA	5%	0%	0%
NMC	35%	15%	10%
LMO	5%	0%	0%
Na-ion	5%	10%	20%

Notes: LFP = lithium iron phosphate; LMFP = lithium manganese iron phosphate; LMO = lithium manganese oxide; Na = sodium; NCA = nickel cobalt aluminium oxide; NMC = nickel manganese cobalt oxide; NMCA = nickel manganese cobalt aluminium oxide.

TABLE A2.4 EV battery chemistry mix for buses by scenario, 2030

[% of vehicle sales]	Technology Stagnation scenario	Current Trends scenario	Increased Innovation scenario
LFP	72%	76%	76%
LMFP	13%	14%	14%
NCA	0%	0%	0%
NMC	15%	9%	5%
Na-ion	0%	1%	5%

Notes: LFP = lithium iron phosphate; LMFP = lithium manganese iron phosphate; Na = sodium; NCA = nickel cobalt aluminium oxide; NMC = nickel manganese cobalt oxide.

TABLE A2.5 EV battery chemistry mix for trucks by scenario, 2030

[% of vehicle sales]	Technology Stagnation scenario	Current Trends scenario	Increased Innovation scenario
LFP	26%	52%	52%
LMFP	4%	8%	8%
NCA	25%	13%	10%
NMCA	15%	6%	5%
NMC	30%	20%	20%
Na-ion	0%	1%	5%

Notes: The same chemistry mix is assumed for all trucks, including the small truck and large truck categories explored in IRENA's model. LFP = lithium iron phosphate; LMFP = lithium manganese iron phosphate; Na = sodium; NCA = nickel cobalt aluminium oxide; NMC = nickel manganese cobalt oxide; NMCA = nickel manganese cobalt aluminium oxide.

TABLE A2.6 Material composition assumed per EV battery type, 2022

[kg/kWh]	LFP	LMFP	NCA	NMCA	NMC	LMO	Na-ion
Graphite	0.96	0.96	0.87	0.57	0.87	0.80	-
Lithium	0.53	0.53	0.59	0.63	0.63	0.59	-
Cobalt	-	-	0.10	0.02	0.14	-	-
Manganese	-	0.31	-	0.04	0.13	1.27	0.41
Copper	0.48	0.48	0.27	0.30	0.30	0.45	-
Phosphorous	0.38	0.35	-	-	-	-	-
Nickel	-	-	0.69	0.72	0.58	-	0.26

Based on: Argonne National Laboratory (2022, 2024), BNEF (2024a) and Maisel *et al.* (2023).

Notes: The values for sodium ion are based on the assumption that by 2030, layered metal oxide technology will represent about 75% of the market share, polyanionic will represent 15% and Prussian blue analogue will represent 10% (Benchmark Minerals, 2023). kg = kilogramme; kWh = kilowatt hour; LFP = lithium iron phosphate; LMFP = lithium manganese iron phosphate; LMO = lithium manganese oxide; Na = sodium; NCA = nickel cobalt aluminium oxide; NMC = nickel manganese cobalt oxide; NMCA = nickel manganese cobalt aluminium oxide.

TABLE A2.7 Material composition assumed per sodium-ion battery type

[kg/kWh]	Layered metal oxide	Polyanionic	Prussian blue analogue	Weighted average
Graphite	-	-	-	-
Lithium	-	-	-	-
Cobalt	-	-	-	-
Manganese	0.54	-	-	0.41
Copper	-	-	-	-
Phosphorous	0.35	-	-	0.26
Nickel	-	-	-	-

Notes: The weighted-average values for sodium ion are based on the assumption that by 2030, layered metal oxide technology will represent about 75% of the market share, polyanionic will represent 15% and Prussian blue analogue will represent 10% (Benchmark Minerals, 2023). Layered metal oxide technology can have numerous compositions, with differing material requirements. This study assumes the material composition of a layered metal oxide with a sodium nickel manganese magnesium titanate oxide cathode based on Gupta *et al.* (2022). kg = kilogramme; kWh = kilowatt hour.

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