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Electrifying road transport with less mining

A global and regional battery material outlook

EYAL LI, GEORG BIEKER, ARIJIT SEN

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International Council on Clean Transportation
1500 K Street NW, Suite 650
Washington, DC 20005

communications@theicct.org | www.theicct.org | @TheICCT

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EXECUTIVE SUMMARY

With the goal of mitigating global warming and reducing harmful air pollution, governments around the world have adopted policies to increase the share of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Aligning the global road transportation sector with the Paris Agreement's goal of limiting global warming to below 2 °C can be achieved by implementing a 100% BEV sales share in major vehicle markets for new light-duty vehicles by 2035 and for new heavy-duty vehicles by 2040, with all other countries completing this transition in the following 5 to 10 years. Although the global road transport sector is not yet aligned with this trajectory, many governments have set targets and are discussing other measures to increase the ambition of vehicle electrification beyond already adopted policies. This acceleration of the transition to BEVs entails a rapid increase in demand for batteries and material supply.

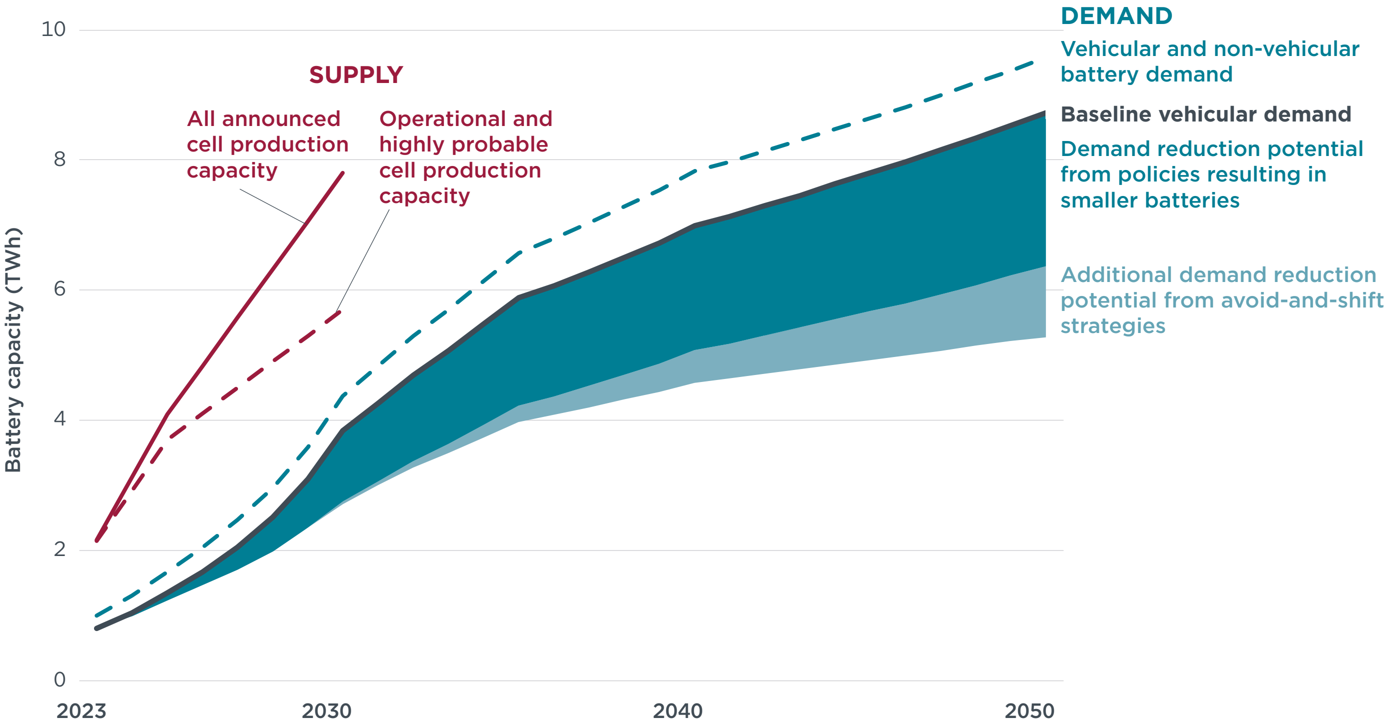
This study projects the demand for BEV and PHEV batteries and battery materials globally and in five focus markets—China, the European Union, India, Indonesia, and the United States—resulting from policies and targets that have already been adopted or are under discussion. This is compared with announced battery cell production and mineral supply capacities. The study covers all segments of road transport, including sales in the light-duty, heavy-duty, and two- and three-wheeler vehicle segments as well as non-vehicular demand. Given the uncertainty surrounding the future development of battery technologies, this study also evaluates sensitivity scenarios of a higher-than-baseline market share of lithium iron phosphate (LFP) batteries and a large-scale application of sodium-ion batteries. Finally, this analysis explores how the establishment of an efficient battery recycling environment, a reduction in the average battery size of passenger BEVs, and a change in vehicle sales through transport demand avoidance and modal shift policies could reduce the demand in raw materials while maintaining a rate of vehicle electrification aligned with announced policies and targets.

Our analysis supports the following conclusions:

Announced battery production plant capacities significantly exceed the projected global road transport and non-vehicular battery capacity demand. As displayed in Figure ES1, both the total announced cell production capacity globally, and the proportion of this capacity that is considered highly probable, exceed projected demand at least until 2030. The majority of current and announced cell production capacities are in China, corresponding to 84% of the global total in 2023 and 67% in 2030. China is thus expected to continue to be a net exporter of batteries in the coming decade. In the European Union, announced cell production capacities could meet an estimated 99% of the region's road transport and non-vehicular battery capacity demand in 2030 if all projects are realized, while production capacities in the United States correspond to 130% of domestic demand in 2030. When considering only facilities that are either already operational and those under construction that are considered highly probable to reach the announced output, capacities in the United States correspond to 103% of domestic demand in 2030, while those in the European Union cover just 72% of road transport and non-vehicular battery capacity demand, highlighting the importance of EU Member States supporting the realization of announced investments. In India and Indonesia, the capacities of the announced cell production plants are comparatively more limited, corresponding to a projected 49% and 44%, respectively, of domestic vehicular battery demand in 2030.

Figure ES1

Annual global battery demand by demand reduction scenario compared with announced cell production capacity



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The scaling-up of battery material supply is projected to catch up with growing demand. Assuming a continuous increase in the average battery size of light-duty vehicles (LDVs) and a baseline scenario for the development of the market shares of LFP batteries, we estimate that mining capacities in 2030 would meet 101% of the annual demand for lithium, 97% of the demand for nickel, and 85% of the demand for cobalt that year, including the demand for these minerals in other applications. When considering a scenario with higher market shares of LFP batteries, the capacities would meet a slightly higher 102% of lithium demand, along with 108% of nickel demand and 103% of cobalt demand. Meanwhile, in a scenario that considers sodium-ion batteries in the future mix, anticipated lithium mining capacities would meet 116% of demand. Finally, assuming the baseline scenario for the development of market shares of battery technologies and a reduction in the average battery size of LDVs by 2030, anticipated mining capacities would meet 130% of the annual demand for lithium, 106% of the demand for nickel, and 100% of the demand for cobalt.

These scenarios highlight that the market can react to low supply or high prices of individual materials by switching to higher market shares of battery technologies containing none or less of these materials. This has already been demonstrated by the ongoing shift to low-cobalt variants of lithium nickel manganese cobalt oxide (NMC) batteries, and by the increasing market share of LFP batteries, which contain neither nickel nor cobalt. At the same time, the comparison shows that the 2030 supply of key battery materials is not yet fully secured. Given the long and uncertain lead times for new mines, industry investments are crucial to ensuring that the growth in mineral mining capacity keeps pace with battery cell, pack, and vehicle production. Similarly, although not assessed in this study, battery-grade mineral refining capacity also would need to scale up to keep pace with increasing battery demand. As refining capacities currently are concentrated in a few regions, building resilient supply chains further entails a broader distribution of capacities.

In the long term, global mineral reserves are sufficient to meet battery demand. In a scenario in which the battery demand through 2050 were met only with lithium-ion battery technologies already commercialized in 2024, and in which no material demand reduction measures were implemented, cumulative material demand would correspond to 49% of current land-based lithium reserves, 38% of nickel reserves, and 38% of cobalt reserves. These projections are likely to be overestimates, for two reasons. First, given rapid improvements in battery technology in recent years, including in technologies with different mineral compositions such as sodium-ion batteries, it is likely that new battery technologies will be commercialized in the future that will reduce aggregate demand for these three minerals. Second, given advances in mineral exploration and mining technology, deposits classified as reserves keep increasing, exemplified by a doubling of lithium reserves in the past five years alone, and it is likely that they will continue to increase in the future.

Despite a general reliance on global material supply chains, domestic reserves can partially meet domestic battery demand. None of the focus markets of this study has sufficient domestic reserves of all key battery materials to meet their projected domestic battery demand. Building resilient international supply chains to secure ample battery-grade minerals is thus necessary to achieve a rate of vehicle electrification aligned with adopted and proposed policies and targets. Yet, individual countries and regions have substantial reserves of certain minerals that can help meet future demand. In China, domestic lithium reserves would meet the cumulative domestic demand from batteries for road transport until between 2040 and 2050, nickel reserves would meet cumulative demand until between 2030 and 2040, and manganese and natural graphite reserves exceed cumulative domestic demand beyond 2050. In the European Union, nickel reserves could meet cumulative domestic demand through between 2030 and 2040, while lithium reserves correspond to only a portion of cumulative domestic demand through 2030. Meanwhile, nickel and cobalt reserves in Indonesia largely exceed cumulative domestic demand through 2050, while India’s rich reserves of natural graphite and manganese massively exceed accumulated demand through 2050. In the United States, current reserves of lithium would meet cumulative domestic demand through between 2030 and 2040, and reserves of manganese are two orders of magnitude higher than cumulative demand through 2050.

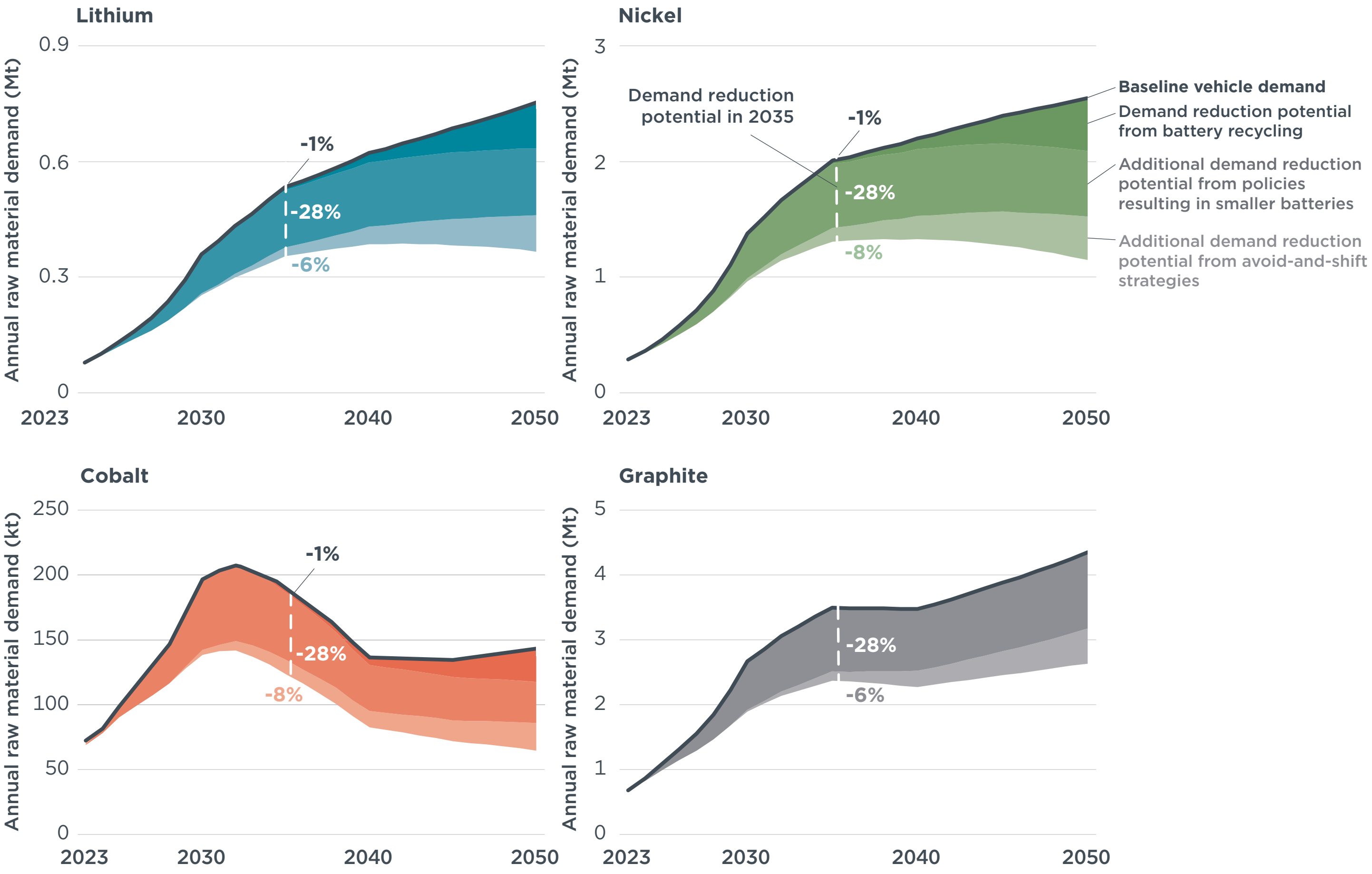
Smaller average battery sizes, especially for light-duty BEVs, can significantly reduce battery and related mineral demand in the near term. Improvements in vehicle energy efficiency can contribute to reductions in average battery sizes for a given vehicle range, while the deployment of more charging facilities can lower the demand for longer-range BEV models. As indicated in Figure ES1, reducing the average battery size of light-duty BEVs by 20% by 2030 compared to today’s level would reduce the annual global battery demand by 28% in 2035 and 27% in 2050 relative to a baseline scenario in which the average battery size increases by 20% (or 10% in the United States) by 2030. As presented in Figure ES2, this translates into an equivalent decrease in demand for lithium, nickel, cobalt, manganese, and graphite in both years. Out of the evaluated measures, this was found to be the most immediate way of reducing battery (and thus raw material) demand.

Battery recycling can reduce the demand for new raw material mining. The study finds that establishing efficient reuse and recycling policies globally would reduce raw material demand for commonly recovered lithium, nickel, and cobalt. However, due to a natural delay between the production of a vehicle battery and its eventual recycling, particularly after use in a second-life application, recycling is expected to become a relevant factor only in the late 2030s. On a global level, recycling could reduce lithium raw material demand by 1% in 2035 and 16% in 2050, and nickel and cobalt demand by 1% in 2035 and 18% in 2050.

Reduced vehicle sales resulting from a less vehicle-dependent transportation system can reduce battery and raw material demand, with impacts growing substantially after 2040. A change in vehicle sales due to avoid-and-shift policies is projected to reduce global battery demand by 6% in 2035 and by 17% in 2050. Mineral demand would be reduced by 6%–8% in 2035 and by 17%–25% in 2050, depending on the mineral. These results highlight the multiple policy levers through which policymakers can reduce raw material demand for BEV and PHEV batteries while still achieving adopted and proposed vehicle electrification policies and targets.

Figure ES2

Annual global raw material demand for lithium, nickel, cobalt, and graphite under the Baseline and demand reduction scenarios, all with the Baseline battery technology shares



Note: Graphite is the only mineral in the figure that is not recycled in the Global Recycling scenario.

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The findings of this analysis suggest that global battery manufacturing and mineral supply chains are not limiting the implementation of vehicle electrification policies and targets that have already been adopted or are currently under consideration. Rather, global mineral supply and cell production capacities are keeping pace with, and partly exceed, the projected demand. Nonetheless, policymakers could consider various measures to reduce the environmental impacts of new raw material mining and refining while maintaining the rate of vehicle electrification. On a regional level, several measures can support a reliable supply of battery cells and raw materials.

Policies reducing the average battery sizes of light-duty BEVs, establishing efficient battery recycling, and implementing avoid-and-shift strategies can help to reduce the demand for new mining. Designing policy measures such as BEV energy efficiency standards or targeting incentives to BEVs with higher energy efficiency and smaller battery capacity can incentivize a shift to vehicles with smaller batteries. In addition to reducing the demand for raw material mining, these policies translate into more affordable BEVs with lower operational costs. To promote the recovery of key materials, policymakers can adopt comprehensive battery recycling policies such as those in the EU's Battery Regulation, which includes extended producer responsibility provisions for the collection and handling of end-of-life vehicle batteries, accessible information sharing requirements on the state of health of the batteries, mineral-specific recovery rates during recycling, and recycled content requirements in the production of new batteries. Transport avoidance and modal shift strategies include planning higher density urban areas, developing cities centered around well-connected public transport, and building safe walking and biking infrastructure.

Predictable BEV adoption policies, incentives for domestic battery material mining, refining, and cell production, and trade agreements with mineral producing countries could help to build reliable supply chains. On the supply side, policymakers can provide more planning security for investments in upstream mining and mineral processing capacity by adopting regulations with clear timelines for increased BEV adoption in all road transport segments. Battery production-linked financial incentives, such as those in the U.S. Inflation Reduction Act, can support domestic manufacturing goals. For the material supply chain, several governments, including Brazil, Canada, the European Union, and the United States, provide or are planning to provide financial incentives to bring new domestic mining and material refining facilities on line. For material demand not covered by domestic reserves, policymakers could negotiate strategic trade agreements with mineral producing countries to secure mineral supply. The environmental and social impact of new material mining, refining, and battery manufacturing can be improved by due diligence standards on environmental and social risks along the value chain, local environmental regulations and social standards, and battery production carbon footprint regulations, as well as by tying public financial incentives to environmental and social criteria.

Setting battery durability standards and supporting research in emerging battery technologies can alter the pathway of vehicle battery-related mineral demand. To encourage research and development on battery technologies based on more abundant materials, such as sodium-ion batteries, and technologies based on materials with a lower environmental impact, governments could consider funding both fundamental and applied research. Further, by establishing high standards for the durability of electric vehicle batteries, governments can better ensure that batteries do not require replacement during their use in BEVs and PHEVs and can be used in second-life applications, such as stationary energy storage for private households, industry, or the power grid, therefore reducing economy-wide battery and material demand.

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INTRODUCTION

Governments around the world are seeking to accelerate the transition to battery electric vehicles (BEVs) to reduce the road transport sector's contribution to climate change and air pollution. The life-cycle greenhouse gas (GHG) emissions of average medium-size BEVs produced today, including emissions related to vehicle and battery manufacturing, fuel and electricity production, and disposal or recycling at retirement, are lower than those of comparable internal combustion engine (ICE) vehicles by about 66% in Europe and Brazil, 60% in the United States, 47% in Indonesia, 37% in China, and 19% in India (Bieker, 2021a, 2021b; Mera et al., 2023; Mera & Bieker, 2023). Similar results have been found for heavy-duty trucks and buses (O'Connell et al., 2023) and two-wheelers (Bieker, 2021b; Mera & Bieker, 2023). With the continuous decarbonization of electricity grids and electricity sources eventually approaching zero emissions, the GHG emissions savings of future BEVs are projected to increase. Plug-in hybrid electric vehicles (PHEVs) and conventional hybrids, in contrast, do not offer a viable long-term pathway to zero emissions, as data on average real-world usage in Europe, the United States, and China indicate that PHEVs are mainly driven on fuel rather than on electricity (European Commission, 2024; Isenstadt et al., 2022; Plötz et al., 2020, 2022).

A 2023 study by the ICCT found that in order to align the global transport sector with the emission reductions needed to limit global warming to 2 °C, major vehicle markets would need to achieve a 100% BEV or hydrogen fuel-cell electric vehicle (FCEV) sales share for new light-duty vehicles (LDVs) by 2035 and for new heavy-duty vehicles (HDVs) by 2040, with all other countries completing this transition in the following 5 to 10 years (Sen & Miller, 2023). To get closer to a 1.7 °C compatible pathway, a broader set of strategies would need to be pursued to further mitigate GHG emissions from the transportation sector, including a reduction in transport demand and policies to encourage modal shifts for passenger and freight transport (Sen & Miller, 2023).

The transition to BEVs in road transport is rapidly increasing the demand for batteries. Global production of batteries for BEVs and PHEVs has increased by a factor of ten, from about 70,000 MWh in 2017 to 730,000 MWh in 2023, and Benchmark Mineral Intelligence (BMI) estimates that it could increase by another factor of ten between 2023 and 2050 (BMI, 2024b). This rapidly growing demand for batteries is mirrored by the growing demand for their raw materials, including lithium, nickel, cobalt, manganese, copper, iron, aluminum, and graphite. A 2023 ICCT report projected that the cumulative demand for these materials from road transport through 2050 will only require a fraction of globally available reserves (Tankou et al., 2023a).[1] However, a rapid scale-up of mining, raw material refining, and battery production capacities is required to keep pace with the exponential increase in BEV and PHEV sales. Moreover, for some of these materials, such as cobalt and nickel, the majority of current mining capacity and known reserves are concentrated in a few regions, resulting in dependencies on far-reaching global supply chains. In response, governments are preparing comprehensive policy platforms to build up domestic battery supply chains and establish reliable trade partnerships. Central to the development of these initiatives is a clear understanding of the projected demand for battery raw materials compared to domestic capacities and of where potential supply bottlenecks may occur.

While the electrification of road transport is needed to mitigate climate change and reduce air pollution, the expansion of battery material mining and refining capacities can create an environmental burden and risk negatively affecting surrounding communities. As mining and refining activities increase, therefore, it is important to improve sustainability and social responsibility along battery material supply chains. Policy approaches that reduce demand

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[1] According to the U.S. Bureau of Mines and U.S. Geological Survey (1976), "reserves are a subset of the estimated global total resources that are discovered and considered economically recoverable at the time of classification."

for battery raw materials while maintaining a fast pace of fleet electrification can help to reduce the social and environmental risks of scaling up supply chains. These approaches may include establishing an efficient battery reuse and recycling system, incentivizing the use of smaller batteries, an overall reduction in private passenger vehicle travel, and more efficient freight transport. To enable consumers, industry, and governments to take steps to improve the sustainability, equity, and resilience of the BEV transition, it is critical to understand key factors that can reduce the demand for new raw material mining.

Several recent studies have projected future material demand for BEV and PHEV batteries. In its annual *Global EV Outlook*, the International Energy Agency (IEA) projects the global supply and demand of battery minerals and discusses how supply and demand factors will shape the BEV transition (IEA, 2024c). Research organizations, including the ICCT, have conducted similar supply and demand forecasts, often focusing on a specific region, a subset of vehicle types, or a shorter timeframe (Shen et al., 2024; Tankou et al., 2023a; Transport & Environment, 2023; Riofrancos et al., 2023; Maisel et al., 2023a). Several of these studies evaluated alternate scenarios to demonstrate how key factors influence the trajectory of battery material demand. Multiple studies have also highlighted the role of vehicle battery sizes, battery recycling, and mode shift strategies in mitigating raw material demand. Other analyses have projected BEV and PHEV battery capacity and mineral demand for transport decarbonization scenarios in specific countries, such as Buchert et al. (2023) for Germany and WWF France, the Institute for Sustainable Development and International Relations' Mobility in Transition Institute, and EY (2023) for France.

This study projects the global demand for raw materials for BEV and PHEV batteries in all road transport vehicle segments until 2050 and compares projected demand to announced mineral supply and cell production capacities. In addition to providing global projections, the study highlights the demand and supply in the major vehicle markets of China, the European Union, and the United States, as well as emerging markets in India and Indonesia. We focus on the demand for lithium, nickel, cobalt, manganese, and graphite. The rate of BEV and PHEV uptake modeled in this analysis considers policies and targets that have been adopted or proposed by global coalitions, regional entities such as the European Union, and national and subnational governments. The projection is based on Sen and Miller (2023), updated with more recent policy developments and targets.

Building on a baseline scenario that assumes the implementation of adopted recycling policies and continued trends in the development of battery sizes and vehicle sales, the study evaluates three pathways through which the same rate of transport electrification could be achieved with less raw material mining: reusing and recycling batteries, implementing policies that reduce fleet-average LDV battery sizes, and reducing the overall demand for private passenger vehicles through transport demand avoidance and mode shift strategies. Further, the analysis incorporates sensitivity scenarios for the development of market shares of battery technologies, highlighting the effect of a faster shift to LFP cathodes and of the potential large-scale application of sodium-ion batteries.

The next section provides an overview of battery technologies, the global battery supply chain, and battery life cycles in the transportation sector. It also describes the supply chains of the five minerals examined in this study: lithium, nickel, cobalt, manganese, and grapite. The methods and data section details how the analysis was conducted, broken down into five steps, each of which addresses a key factor determining battery material demand: vehicle sales, battery capacity, battery technology, battery material intensity, and recycling and reuse. The results section presents our projections at the global level and for the five focus markets of our analysis, while the discussion section describes the limitations of our study and compares its results with the existing literature. Lastly, the policy implications section highlights takeaways for policymakers and suggests measures to advance resource-efficient and circular battery supply chains as a pillar of transport decarbonization.

BACKGROUND

BATTERY TECHNOLOGIES

Lithium-ion batteries are the predominant technology for BEV and PHEV batteries. A lithium-ion battery cell is composed of a cathode and an anode, between which lithium ions are shuttled during charging and discharging, and an electrolyte solution that facilitates the transport of the lithium ions. A separator between the anode and cathode prevents a short-circuit between the two electrodes. Lithium-ion battery cells also require current collector foils, which are currently made from copper at the anode and aluminum at the cathode.

For the cathode, the materials most commonly used in vehicles today are lithium nickel manganese cobalt oxide (NMC), lithium iron (ferro) phosphate (LFP), and lithium nickel cobalt aluminum oxide (NCA). While batteries using NMC or NCA cathodes have a higher specific energy, thus enabling a higher driving range for a given battery mass, LFP batteries are cheaper per kilowatt-hour of battery capacity and more durable (Preger et al., 2020). Within the family of NMC batteries, the relative shares of nickel, cobalt, and manganese vary. For instance, while NMC111 contains equal shares of the three elements, NMC622 and NMC811 use a 6:2:2 ratio and an 8:1:1 ratio, respectively. A higher nickel share results in higher specific energy (Hettesheimer et al., 2023); in recent years, the global market has shifted towards battery chemistries with higher nickel content, as illustrated by the evolution from NMC111 to NMC955 batteries. As indicated by their names, all cathode materials contain lithium, while only NMC and NCA cathodes contain nickel and cobalt. Anodes are primarily composed of graphite, though manufacturers have begun to add small proportions of silicon, which increases the battery's specific energy, given that one kilogram of silicon can store about ten times more lithium ions than a kilogram of graphite (Sekine, 2023). The key materials used in current lithium-ion batteries are thus lithium, nickel, manganese, cobalt, graphite, copper, and aluminum. The material content of different battery technologies is listed in Table A4 in the appendix.

Beyond lithium-ion batteries, two emerging technologies could affect the material demand of BEV and PHEV batteries: sodium-ion batteries and solid-state batteries. Sodium-ion batteries are similar to their lithium-based equivalents but differ in anode and cathode materials; they can also use aluminum instead of copper as a current collector at the anode and the cathode. At the anode, sodium-ion batteries use hard carbon instead of graphite. In the cathode, the majority of planned production capacities are for layered oxide cathodes (BMI, 2023a), for which a range of variants are being investigated (Zuo et al., 2023). Polyanionic and Prussian blue analogues could also be used as cathode materials, but they correspond to only a small proportion of planned sodium-ion battery production. Sodium-ion batteries are expected to be cheaper per kilowatt-hour of battery capacity than lithium-ion, but with lower specific energy. Mass production of sodium-ion batteries started in 2023 and several Chinese automakers have announced BEV models using sodium-ion batteries (Kang, 2023; Westerheide, 2023).

Solid-state batteries use the same cathode materials as lithium-ion batteries, but use lithium metal instead of graphite in the anode. In effect, they require the same amount of key raw materials per kilowatt-hour of battery capacity as lithium-ion batteries, only with higher demand for lithium and no demand for graphite. This could increase the specific energy by up to 50% on a cell level (Betz et al., 2018). Because the lithium metal anode corrodes when in contact with liquid electrolytes, these batteries use a solid electrolyte, which requires the development of new production processes. For these reasons, solid-state batteries are expected to come at higher costs per kilowatt-hour of battery capacity compared to lithium-ion batteries. The development of solid-state batteries is still at an early phase, and the announced start of mass production of the technology has been postponed many times. Due to uncertainty regarding when this technology will be available on the mass market, a high similarity in material demand, and possible limitations in its economic competitiveness with conventional lithium-ion battery technologies, solid-state batteries are not considered in this study.

Current market shares of battery technologies, possible future market trends, and their material demand on a per kilowatt-hour basis are discussed under steps 3 and 4 in the methods and data section.

BATTERY SUPPLY CHAIN

The supply chain of BEV and PHEV batteries can be categorized into three phases: (1) raw material mining; (2) processing and refining of raw material and production of cathode and anode material; and (3) cell production and battery module and pack assembly. Once today's BEVs and PHEVs reach their end of life, the recovery of material through recycling will become an important source of battery materials. Currently, most upstream mining, mineral processing, and battery cell production capacities are concentrated in a few countries. This section provides an overview of the geography of the current battery supply chain and how it could change in the future.

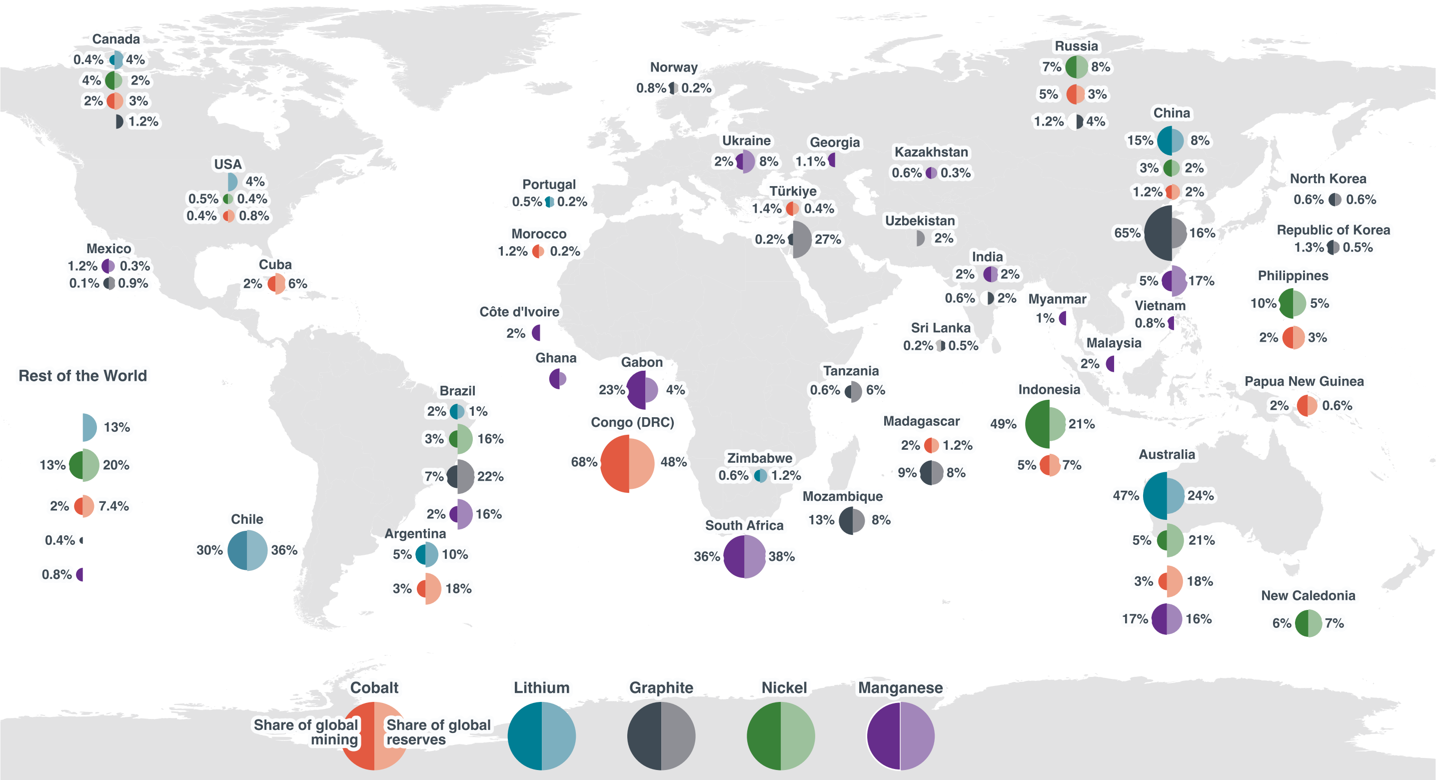
Mineral reserves and mining

When describing the potential of mineral deposits, resources must be distinguished from reserves: Resources include all concentrations of materials from which an extraction is potentially economically feasible, while reserves are the portion of resources that have been demonstrated to meet the grade, quality, thickness, and depth requirements of the mining practices and economics at the time of determination (U.S. Geological Survey, 2024). An increasing demand for specific minerals can influence their market prices, lead to discoveries of new resources, and spur the development of novel mining and processing techniques. Each of these developments can contribute to increases in mineral reserves.

Figure 1 presents the location of the main reserves of lithium, nickel, cobalt, manganese, and natural graphite by country, indicating select countries' shares of global reserves (U.S. Geological Survey, 2024). As discussed in the results section, global reserves of key minerals have grown over the last decade and continue to increase (U.S. Geological Survey, 2024); this figure should therefore be considered a snapshot of global reserves as of 2024, and additional countries may appear on the map in the future. For example, Bolivia and India have large resources of lithium, but these have not yet been classified as reserves. The figure also presents the shares of global mining of these minerals occuring in each country. Comparing shares of mineral reserves against shares of current mining indicates which countries could expand mining capacities for battery materials.

Figure 1

Global distribution of lithium, nickel, cobalt, manganese, and natural graphite reserves and mining in 2023



Note: Countries displayed contain more than 0.5% of either reserves or mining.

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For lithium, extraction from hard rock resources in Australia accounts for nearly half of the world's mining activity (IEA, 2022). However, mineral explorers in Chile, Argentina, and Bolivia have identified rich lithium brine resources in the region where their borders meet, commonly known as "the lithium triangle." Though home to the largest volume of lithium resources globally, Bolivia has not yet scaled up industrial lithium production in comparison with its two southern neighbors (Ramos, 2023). Outside of these regions, China has significant reserves of lithium in hard rock deposits, and accounted for around 15% of the world's lithium mining in 2023 (U.S. Geoglocial Survey, 2024). The United States is home to about 4% of global lithium reserves, concentrated in clays and geothermal and oil field brines. According to BMI (2022), global lithium mining capacity is projected to increase by 237% between 2023 and 2030. During this period, the share of mining in Argentina, the United States, Zimbabwe, and Canada is projected to grow, while the relative shares in Australia, Chile, and China are expected to decrease.

Nickel reserves are located primarily in Australia, Indonesia, Brazil, the Philippines, the French overseas territory of New Caledonia, and Russia. The bulk of nickel mining currently occurs in Indonesia (49%), the Philippines (10%), and Russia (7%). Indonesia's nickel mining capacity is expected to grow in the near term: BMI (2023b) projects that 66% of refined nickel production in 2030 will occur in Indonesia.

Almost 70% of the world's cobalt is mined in the Democratic Republic of the Congo. Australia has the second largest cobalt reserves with about 18% of the global total, but accounts for 3% of current production. Indonesia has emerged as a leading cobalt producer due to the growth of high-pressure acid leaching technology.

Manganese ore mining is located mainly in South Africa, Australia, Gabon, and China, although resources are more geographically dispersed than other battery materials (U.S. Geological Survey, 2024).

Graphite can be mined or synthetically produced. Although the two materials are similar, slight structural differences allow natural graphite anodes to have higher energy capacities, while synthetic graphite anodes can endure longer lifetimes (BMI, 2023d). In 2023, about three-quarters of battery anodes contained synthetic graphite, with the rest containing natural graphite (BMI, 2023b). For natural graphite, about 65% of global mining occurs in China. Natural graphite reserves are relatively common, however; Türkiye, Brazil, Mozambique, Madagascar, and Russia also hold sizeable reserves. As identified by Ramji and Dayemo (2024), the high quality of deposits in India could make the country a key natural graphite producer in the future. Synthetic graphite, in contrast, is produced by heat treatment of petroleum byproducts, including coke, coal tar pitch, or oil.

Mineral refining and active material production

Raw minerals, such as mineral ores, need to be processed and refined into battery-grade chemicals. These processes correspond to a significantly larger share of a battery's life-cycle GHG emissions than the mineral extraction (IEA, 2024c). Mineral refining capacity is concentrated in a few regions and is typically in the hands of a few companies, some of which conduct both mining and refining. The distribution of battery-grade mineral refining capacity differs significantly from the distribution of raw mineral mining. In 2023, China was home to a large proportion of battery-grade lithium, nickel, cobalt, and natural (and synthetic) graphite refining capacity.

For lithium, the material processing and refining processes depend on the type of deposit the mineral was obtained from. Lithium from brine deposits, such as in Chile, can be relatively easily processed into lithium carbonate, while lithium from hard rock deposits can be processed either into lithium carbonate or lithium hydroxide. Five companies operate about three-quarters of global lithium refining capacity. In 2019, about 60% of lithium refining was located in China, with about 30% in Chile and 10% in Argentina (IEA, 2021).

Nickel reserves are common in two forms: sulfide and laterite deposits. Sulfide deposits, located primarily in Russia, Canada, and Australia, are relatively easier to process into battery-grade, Class-1 nickel with a purity standard of 99.8% or higher. Laterite deposits, located mainly in Indonesia, the Philippines, and New Caledonia, require significant energy inputs to be processed into battery-grade nickel. The Indonesian government recently adopted policies to increase battery-grade nickel processing capacity to develop an integrated battery supply chain (Saegert et al., 2022). It is estimated that China accounted for about 37% of Class 1 nickel processing in 2019, with Indonesia and Japan accounting for around 20% and 8%, respectively (IEA, 2021).

Cobalt-containing ores must be processed into cobalt sulfate as an input for NMC cathode material production. In 2019, about 65% of cobalt sulfate processing was located in China, 10% in Finland, and 5% in Indonesia (IEA, 2021). Manganese is typically refined into manganese sulfate, 90% of which is produced in China, for use in battery cathode production (IEA, 2022). Natural graphite, meanwhile, must be refined into spherical graphite to be used in lithium-ion batteries. Nearly all spherical graphite is refined in China (BMI, 2023c).

After the raw materials are processed and refined, they are used to produce the anode and cathode materials. Cathode production is also highly concentrated, with seven companies responsible for 55% of cathode material production, most of which takes place in China, South Korea, and Japan. Anode material production is even more concentrated, with six companies accounting for two thirds of capacity; China accounts for an estimated 93% of anode production (IEA, 2022).

Cell production, module and pack assembly

During cell production, the cathode and anode active materials are mixed with binders and casted on aluminum and copper current collector foils. These foils are then coupled with a separator that is soaked with a liquid electrolyte, and a cell housing is added. In 2023, 84% of cell production capacities were in China, 5% in the European Union, and 6% in the United States (BMI, 2024a). By 2030, as discussed in the results section, these shares are expected to be 67% in China, 10% in the European Union, and 14% in the United States. Cell production is capital intensive and global production capacity is highly concentrated in a few large companies. In 2023, three firms collectively accounted for 53% of global cell production: China-based Contemporary Amperex Technology Co., Limited (CATL), China-based Build Your Dreams (BYD), and South Korea-based LG Energy Solution (BMI, 2023). CATL alone was involved in 33% of global cell production in 2023.

Individual battery cells are typically packed into modules, which are further combined into packs by adding sensors and a battery management system in a housing shell. However, manufacturers are increasingly assembling battery packs without modules to increase the proportion of active material in the battery, thereby increasing energy density. Battery pack assembly is performed either by cell manufacturers, pack manufacturers, or by automakers.

Scaling up the battery supply chain

Different parts of the battery supply chain require different lead times to scale up operation. Battery cell production facilities, for example, generally can be built and put into operation within 1 to 4 years, depending on the size and experience of a battery manufacturer (IEA, 2022).

Scaling up mining facilities, in contrast, entails much longer and more uncertain lead times. For lithium mines, lead times between initial discovery of the deposit to the start of production are typically shorter than those for other battery minerals, varying between 4 years for hard rock mines in Australia and 7 years for brine extraction sites in South America (IEA, 2021). In contrast, the lead time for nickel sulfite mines require an average of 13 years, and nickel laterite mines require an average of 20 years (IEA, 2021). The average lead time of copper mines is around 17 years with a median of 12 years (IEA, 2023b; Heijlen et al., 2021). Since cobalt is typically mined as a byproduct of nickel or copper mining, the lead times of cobalt mines match those of nickel and copper mines. The relatively long lead times for mines are a result of the need to secure financing, complete feasibility studies, and carry out engineering and construction work, as well as the sometimes-lengthy permitting process. However, some new mines—such as the Nova-Bollinger cobalt, copper, and nickel mine in Australia—can have a much shorter lead time of 5 years or less from mineral discovery to start of production, with an additional 3–4 years to achieve nameplate production capacity (IEA, 2023b). Adequate and early investments in upstream mining and mineral refining development are necessary to avoid capacity bottlenecks.

Supply chain risks and resilience

The geographic concentration of certain nodes of the supply chain in a few regions can make it vulnerable to disruptions from geopolitical tensions, changes in political and economic conditions, and shifting trade partnerships, among other factors. Such disruptions can lead to bottlenecks that have a ripple effect throughout the battery supply chain, resulting in supply and price volatility and ultimately slowing down the transition to BEVs. As discussed in the policy implication section, many countries have responded to supply chain risks by encouraging the integration of domestic supply chains and fostering partnerships with resource-exporting countries.

BATTERY REUSE AND RECYCLING

As described in a recent ICCT study by Tankou et al. (2023a), the recycling of BEV and PHEV batteries allows for the recovery of key materials. This can create jobs while reducing demand for new raw material mining and dependence on international supply chains. The scope of materials that can be recovered depends on the applied recycling processes. Processes starting with pyrometallurgical steps, followed by hydrometallurgical methods, usually only allow the recovery of nickel, cobalt, manganese, and copper, meaning lithium, graphite and aluminum are not recovered. Processes without pyrometallurgical steps typically start with a mechanical treatment of the batteries to obtain a mixture of anode and cathode powder. Using a hydrometallurgical process to recover materials from the anode and cathode powder allows the recovery of lithium and aluminum in addition to nickel, cobalt, manganese, and copper. Graphite, however, is still not recovered with hydrometallurgical recycling. In a third type of recycling process, referred to as direct recycling, the material structure of the cathode and anode materials are retained and regenerated for use in new batteries. This recycling process has, to date, only been demonstrated on a pilot scale. The environmental impact of the three recycling processes can differ significantly, with processes that include a pyrometallurgical step involving the highest risks of air and water pollution. With the recovery of the key minerals, however, recycling avoids the mining of more raw materials, and can therefore generally provide environmental benefits (Tankou et al., 2023a). Nonetheless, clear environmental regulations are needed to ensure low environmental impacts of recycling plants.

Prior to recycling, it is expected that a significant share of BEV batteries can be used in a second-life application even though the vehicle itself has reached its end of life. This second-life use, such as for stationary energy storage in household, industry, or grid applications, reduces the raw material demand for batteries that may otherwise have been produced.

Tankou et al. (2023a) provide an overview of battery reuse and recycling policies in major BEV and PHEV markets. Among these, the European Union, and to a lesser extent China, are spearheading efforts to develop frameworks for ensuring efficient collection of end-of-life vehicle batteries and the recovery of key battery materials from recycling. In the European Union, the Battery Regulation, adopted in 2023, assigns responsibility for the collection and recycling of end-of-life vehicle batteries to automakers and mandates the recovery of defined shares of lithium, nickel, cobalt, and copper during the recycling of end-of-life batteries (Regulation [EU] 2023/1542). In parallel, the regulation mandates the use of defined proportions of recycled material in the production of new batteries. This latter provision ensures that materials are recovered in a high purity, allowing them to be reused in batteries and thus preventing downcycling (Tankou et al., 2023a). Further, the Battery Regulation's battery passport provisions require the collection and disclosure of data on the battery. This allows battery processors to determine the state of health of used batteries and thereby facilitate the assignment of potential second-life applications without performing costly tests.

As in the EU Battery Regulation, China has adopted policies making BEV manufacturers responsible for the collection and recycling of end-of-life batteries. Further, recycling companies can qualify for a voluntary certification when meeting element-specific recovery rates for nickel, cobalt, manganese, and lithium (Ministry of Industry and Information Technology, 2019). China has also developed a battery passport platform that facilitates the traceability of batteries throughout their lifetime, increasing the likelihood they are collected and recycled at the end of their first application (Reuters, 2018).

RESPONSIBLE MINING

The raw material mining, processing, and refining stages of the battery supply chain entail the risk of negative social and environmental impacts for workers and local communities. These impacts may include the displacement of residents, health impacts from working conditions and air and water pollution, and human rights abuses (Avan et al., 2023). For instance, in the Democratic Republic of the Congo, unregulated artisanal mining operations, which account for about 20% of total cobalt mining in the country according to the Congolese government, have a record of child labor and hazardous working conditions (Amnesty International, 2016). In large-scale authorized mining operations, advocacy organizations have reported excessive working hours, low wages, and work tasks that leave workers with debilitating injuries (RAID, 2021; Houreld & Bashizi, 2023). Moreover, in mines and surrounding communities, exposure to dust containing cobalt and other metals has led to high rates of respiratory diseases among workers and residents (Amnesty International, 2016).

With strong due diligence regulations and governance arrangements in place, mining activities can stimulate the economy, create jobs, and support infrastructure development, thereby improving local economic conditions and community welfare (Mancini & Sala, 2018). Starting in 2025, the EU Battery Regulation's due diligence obligations will require all companies selling batteries in the European Union to identify, report and mitigate social and environmental risks in the supply chain for cobalt, lithium, nickel, and natural graphite. Additional policies to reduce the social and environmental risks of mineral supply chains can build on experience from past responsible mining programs, such as those led by the Initiative for Responsible Mining Assurance. Moreover, regulations mandating the availability of data related to raw material supply chains can increase transparency in international mineral markets, helping regulators mitigate such harms.

METHODS AND DATA

This section describes the data sources and key assumptions used for our projection of the future demand for battery production capacities and raw material supply. The analysis was based on a chain of calculation steps, starting from the estimated sales of BEVs and PHEVs, which were combined with segment average battery capacities, battery technology market shares, material intensity for each of these technologies, and potential raw material demand reduction due to battery recycling. We built on the battery material demand estimate methodology used in earlier ICCT studies, including global demand estimates by Tankou et al. (2023a) and Slowik et al. (2020) and regional demand estimates for the United States (Shen et al., 2024) and India (Gode et al., 2021). Detailed descriptions of assumptions and data sources can be found in the appendix.

STEP 1: VEHICLE SALES

The development of sales of BEVs and PHEVs modeled in this analysis was derived from projected sales of vehicles of all powertrain types, multiplied by the BEV and PHEV sales shares that correspond to current and proposed policies and targets. For sales of all powertrain types, the analysis compared a Baseline scenario with an Avoid-and-Shift scenario showing the impact of lower passenger vehicle and freight transport demand. In both vehicle demand scenarios, the same sales shares of BEVs and PHEVs were considered.

This study projected sales of BEVs and PHEVs in three segments: two- and three-wheelers; light-duty vehicles (LDVs), comprising light-duty passenger and light commercial vehicles; and heavy-duty vehicles (HDVs), which include medium-duty trucks (MDTs), heavy-duty trucks (HDTs), and buses. Sales for each category were estimated with the ICCT’s Roadmap model (ICCT, 2022). Two- and three-wheelers refer to any two- or three-wheeled vehicle that can reach velocities above 25 km/h. For all markets except Europe, India, and the United States, two- and three-wheeler sales data were based on the 2023 version of the IEA’s Mobility Model (IEA, 2024c). In the ICCT’s Roadmap model, MDTs are categorized as trucks with a gross vehicle weight (GVW) between 3.5 and 15 tonnes and HDTs have a GVW over 15 tonnes (ICCT, 2022). These definitions of MDTs and HDTs may differ from those used by regulatory agencies.[2] Notably, this study assumed that all zero-emission HDVs are battery electric, rather than a mix of hydrogen fuel-cell electric and battery electric vehicles. This assumption was based on the current dominance of battery electric over fuel-cell electric HDVs in China (Mao et al., 2023) and Europe (Mulholland et al., 2024), and the projected total cost of ownership advantage of battery electric trucks over other HDV technologies in China (Mao et al., 2021), the European Union (Basma & Rodríguez, 2023a), and the United States (Basma et al., 2023). This analysis thus provides an upper bound for battery demand by assuming 100% of zero-emission HDVs are BEVs.

Shares of BEVs and PHEVs in these vehicle sales build on the Political Momentum scenario by Sen and Miller (2023), which accounts for the impacts of policies and targets adopted or proposed as of March 2023. Specifically, this scenario considers policy proposals and BEV targets announced by global coalitions, regional entities such as the European Union, and national and subnational governments. For this paper, a handful of additional targets and more recent policy developments were considered. These included the final rule of the U.S. multi-pollutant emission standards for light-duty and medium-duty vehicles; the unofficial target proposed by the China Society of Automotive Engineers and China Automotive Research Center’s *Automotive Industry Green and Low-Carbon Development Roadmap 1.0* that 60% of combined new sales

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[2] The U.S. Environmental Protection Agency, for example, defines MDTs as vehicles with a GVW between 10,001 and 26,000 lb (4.54 and 11.79 tonnes), and HDTs as vehicles above 26,000 lb (11.79 tonnes).

of cars, buses, and trucks be new energy vehicles (NEVs) by 2030; India's target that 80% of new two- and three-wheeler sales be BEVs by 2030; and Indonesia's target that all new sales of two- and three-wheelers and LDVs be fully electric by 2040 and 2050, respectively. As in Sen and Miller (2023), the scenario also includes the European Union's 2023 LDV and 2024 HDV CO_2 standards, the U.S. Phase 3 GHG emission standards for HDVs, and the adoption of the Advanced Clean Cars II and Advanced Clean Truck regulations by additional states.

The Political Momentum scenario can be understood to reflect heightened political ambition to decarbonize the road transport sector. However, it does not entail a level of ambition that aligns the global on-road transport sector with a pathway of limiting global warming to below 2 °C, as committed to in the Paris Agreement. As presented in Sen and Miller's (2023) Ambitious scenario, this target would require major vehicle markets to achieve a full electrification of new LDV and HDV sales by 2035 and 2040, respectively, and all other markets follow 5 to 10 years later. The Political Momentum scenario's BEV and PHEV sales shares generally reflect the development of BEV and PHEV sales needed to meet adopted policies and targets and those currently under consideration; market dynamics accelerated by these policies and targets, in particular BEVs reaching and surpassing purchase price parity with conventional ICE vehicles earlier, are not covered. However, market dynamics resulting from an earlier set of policies, as reflected in Sen et al. (2023)'s Baseline scenario, are included. In particular, these dynamics result in increasing BEV sales shares among two- and three-wheelers in certain regions without specific policies or targets.

Baseline scenario

In the Baseline scenario, detailed in Table A2 in the appendix, global annual LDV sales of all powertrain types increase by 68%, from 89 million in 2023 to 150 million in 2050. While LDV sales increase marginally in the United States, they are projected to increase by 61% in the European Union, 86% in China, 93% in India, and by a factor of 3 in Indonesia. Over the same period, global sales of two- and three-wheelers are projected to increase by 55% from 79 million to 122 million, bus sales are projected to more than double from 1.2 million to 2.6 million, and MDT and HDT sales combined are expected to double from 4.5 million to 9 million.

Figure 2 displays projections of global BEV and PHEV sales, which were determined by combining the vehicle demand from the Baseline scenario with the projected BEV and PHEV sales shares across the segments and markets. Between 2023 and 2050, global sales of electric two- and three-wheelers are projected to increase from 17 million to 96 million, sales of light-duty BEVs and PHEVs increase from 15 million to 102 million, and sales of electric HDVs increase from 0.3 million to 4.7 million. The number of annual BEV and PHEV sales in all segments are projected to increase by about 6 times between 2023 and 2050 to reach 203 million.[3] By segment, between 2023 and 2050, annual BEV and PHEV sales are expected to grow by a factor of 6 among two- and three-wheelers, of 7 among LDVs, and of 17 among HDVs.

In 2023, battery electric two- and three-wheelers are projected to make up one of every two BEV and PHEV sales globally. In 2050, despite the rapid growth of BEV sales in the light-duty vehicle segment—which grow by a factor of 9 between 2023 and 2050—sales of electric two- and three-wheelers with lithium-ion batteries are still projected to make up 47% of global BEV and PHEV sales. This is largely due to lithium-ion battery electric two- and three-wheelers reaching price parity with ICE models earlier than for battery electric passenger cars.

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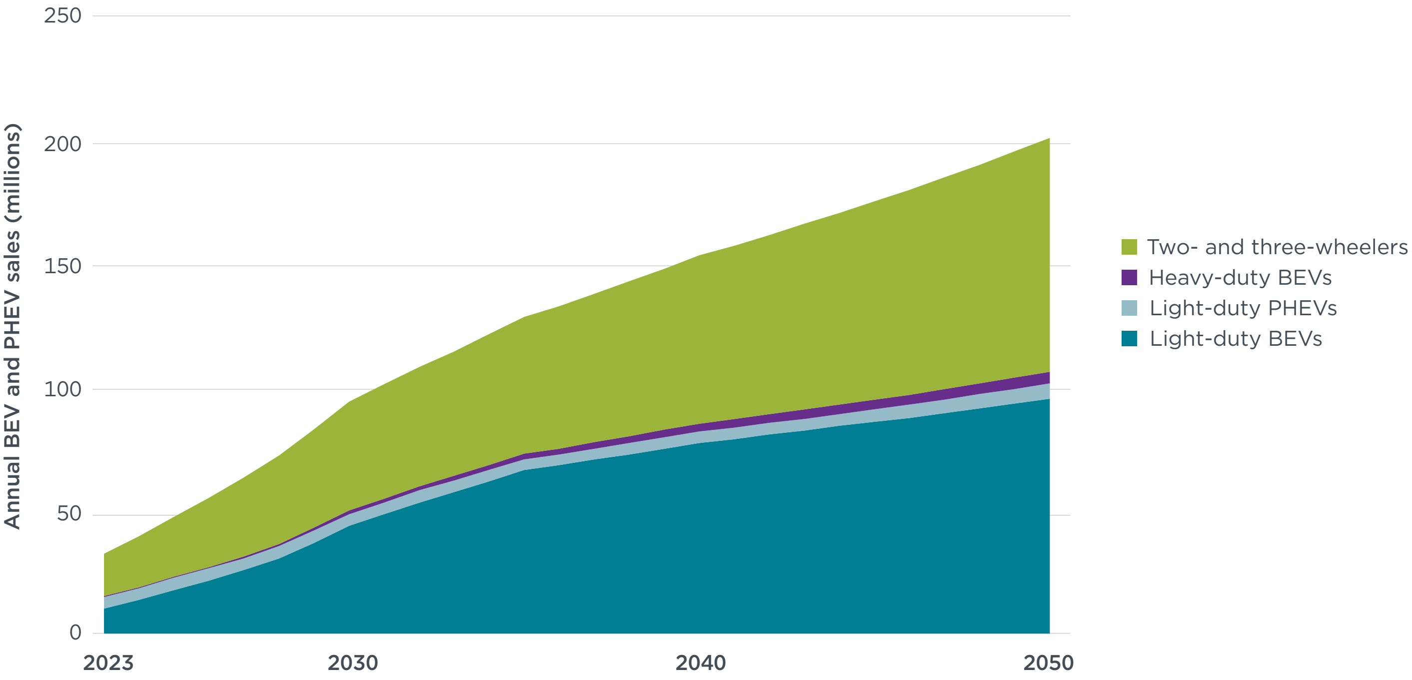
[3] BEV and PHEV sales data in this study include electric two- and three-wheelers with lead-acid batteries. However, only the demand for lithium-ion and sodium-ion batteries is presented in this analysis.

Figure 2

Annual global sales of light-duty BEVs and PHEVs, heavy-duty BEVs, and two- and three-wheeler BEVs



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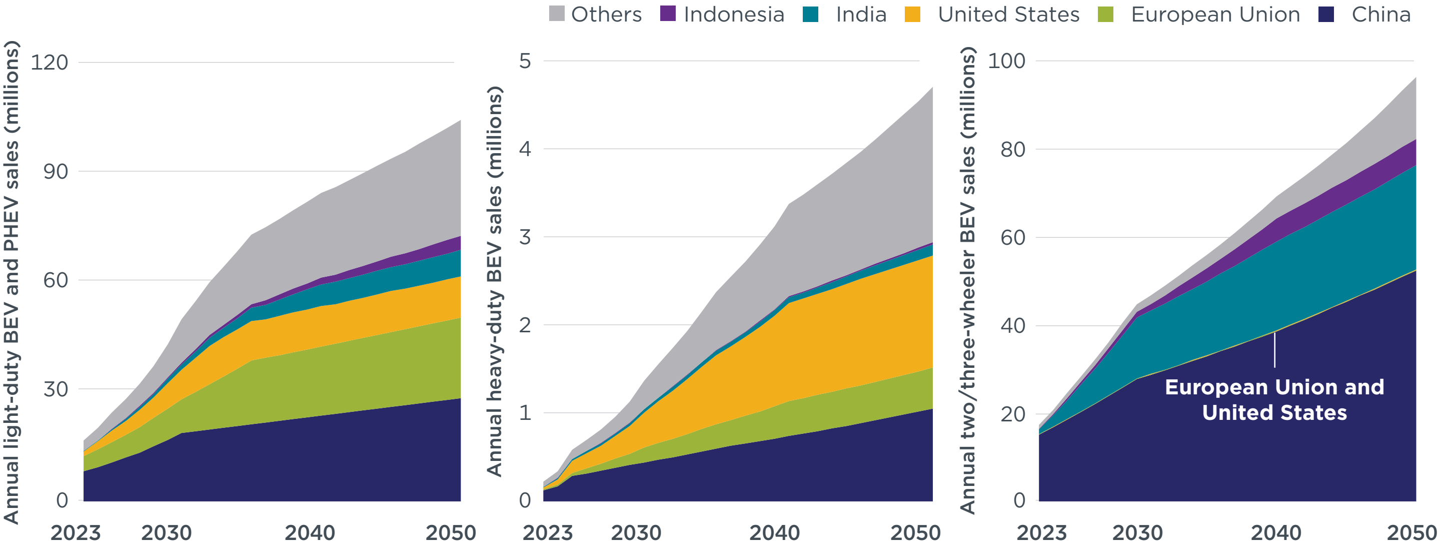
Projected sales of light-duty BEVs and PHEVs, heavy-duty BEVs, and two- and three-wheeler BEVs in the five focus markets are displayed in Figure 3. Until 2050, annual light-duty BEV and PHEV sales are projected to grow by a factor of 3 in China, 8 in the European Union, and 8 in the United States. In the emerging markets of India and Indonesia, annual light-duty BEV and PHEV sales are projected to grow by factors of 96 and 406, respectively. Battery electric two- and three-wheelers, meanwhile, are estimated to grow rapidly in all markets except the United States and European Union, where historic sales of these vehicles are low compared to other markets.

Figure 3

Annual sales of light duty BEVs and PHEVs (left), heavy-duty BEVs (center), and two- and three-wheeler BEVs (right), by market



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Avoid-and-Shift scenario

The Avoid-and-Shift scenario evaluates how the future growth of vehicle sales could be impacted by avoid-and-shift policies affecting both passenger and freight transport. It is based on the ICCT Shift scenario as described by Sen and Miller (2023).

For passenger transport, the ICCT Shift scenario is a modified version of the International Transport Forum (ITF)'s High Ambition scenario (ITF, 2023). It considers a reduction of private passenger car travel, which can be achieved through a shift to other modes of transport and avoided overall transport demand, such as through densification of urban design, pricing mechanisms, and other measures. The ICCT Shift scenario modifies the original ITF High Ambition scenario by considering a larger rate of reduction in private passenger car kilometers (Sen & Miller, 2023). The Avoid-and-Shift scenario in this study translates the reduction in passenger car activity in the ICCT Shift scenario relative to the ITF Baseline scenario into a reduction in vehicles sales.

Table A1 in the Appendix displays the difference in passenger travel activity in 2050 between the ICCT Shift scenario and the ITF Baseline scenario by mode of passenger car transport and region. The table displays the average values across all metropolitan areas in the selected regions, as well as for the global average.

The Avoid-and-Shift scenario entails two important assumptions related to passenger transport. First, although the ITF scenarios only account for transport activity in metropolitan areas, the Avoid-and-Shift scenario considers these changes to be representative of market-wide trends. As a shift from private passenger car transport to other transport modes can be more challenging in rural regions, this assumption is expected to result in an overestimation of the change in activity. A second assumption is that the changes in activity are solely reflected in a change in vehicle sales. Potential changes in activity on a per-vehicle basis are thus neglected. The modeling is therefore likely to overestimate the potential effect of avoid-and-shift policies on vehicle sales because such measures would likely also impact the mileage of existing vehicles. Table A2 in the appendix displays the vehicle sales of all powertrain types per market and segment in 2023 and compares the respective 2050 sales for the Baseline and Avoid-and-Shift scenarios in our study. Relative differences in vehicle sales between the Baseline and Avoid-and-Shift scenarios are assumed to build more slowly at first before accelerating in later years. Notably, sales of buses and two- and three-wheelers are not changed in the Avoid-and-Shift scenario compared with the Baseline scenario.

For freight transport, the ICCT Shift scenario as described by Sen and Miller (2023) is based on the 2 °C compatible and well-below 2 °C compatible scenarios in IEA's *Future of Trucks* report (IEA, 2017) and considers a decrease in vehicle kilometers traveled and an increase in the load factor. To translate the difference in freight transport activity between the IEA Baseline and ICCT Shift scenarios into vehicle sales, it is assumed that the mileage on a per-vehicle basis remains constant, meaning that the decrease in vehicle kilometers traveled and increase in the load factor are solely reflected in a decrease of vehicle sales. Table A2 displays the 2023 and 2050 sales (of all powertrain types) of light commercial vehicles, MDTs, and HDTs for the Baseline and Avoid-and-Shift scenarios. For the share of these sales that are BEVs, the Sen and Miller (2023) Political Momentum scenario is considered.

STEP 2: BATTERY CAPACITY

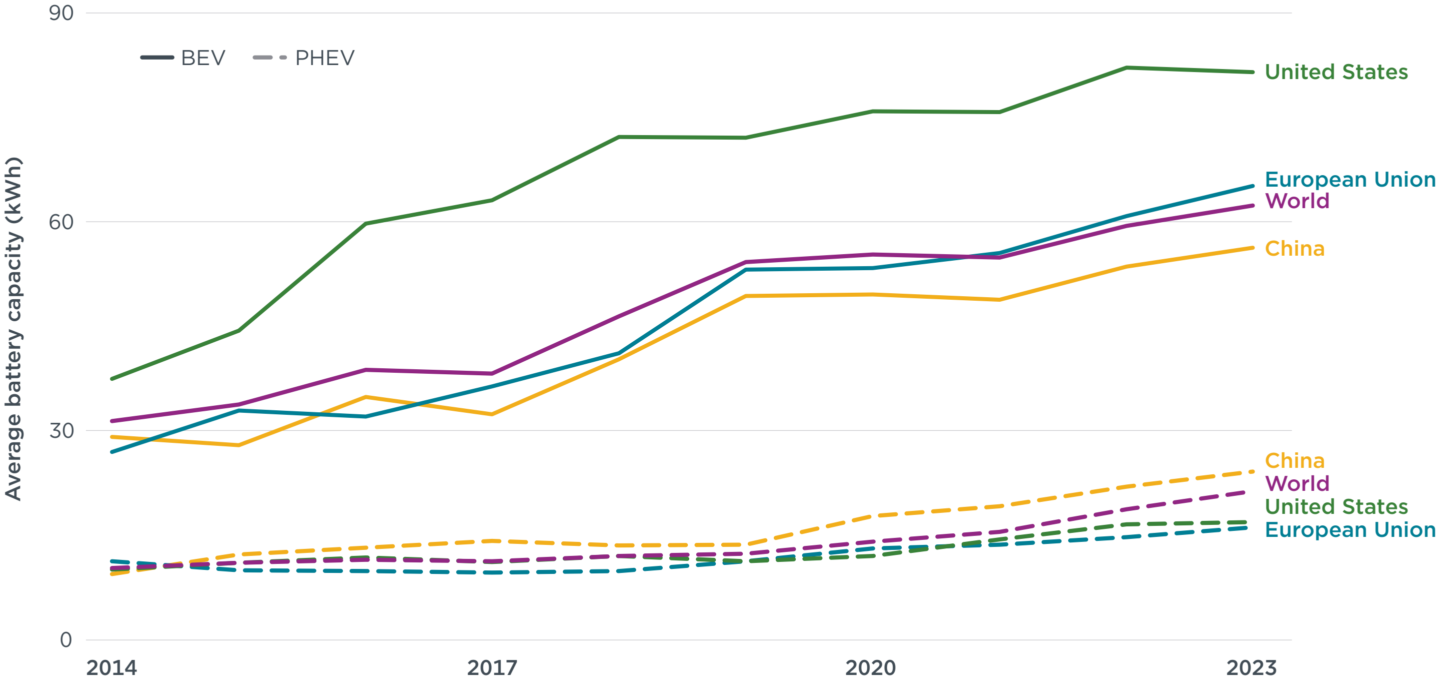
Light-duty vehicles

Figure 4 presents historical sales-weighted average battery capacities of light-duty BEVs and PHEVs, based on EV Volumes (2024). For BEVs, the average battery capacity increased significantly between 2018 and 2023, from 40 kWh to 56 kWh in

China (+40%), from 41 kWh to 65 kWh in the European Union (+59%), and from 72 kWh to 82 kWh in the United States (+14%). Global average BEV battery capacity increased from 46 kWh in 2018 to 62 kWh in 2023 (+35%). In India and Indonesia, where BEV sales are still in a comparatively nascent stage, the 2023 sales-weighted average battery capacity was at 34 kWh and 59 kWh, respectively.[4]

Figure 4

Trends in average battery capacity of light-duty BEVs and PHEVs globally and in China, the European Union, and the United States



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For the major BEV markets of China, the European Union, and the United States, Figure 5 presents the development of the sales-weighted average battery capacity in segments with the highest BEV sales. The sales-weighted average battery capacities for light-duty BEVs and PHEVs in China are based on data from EV100 (2024). The evaluation for the European Union is based on sales data from the European Environment Agency (2023) and vehicle specifications data from the Allgemeiner Deutscher Automobil-Club (2023). The U.S. data are from EV Volumes (2024).[5] Almost all vehicle segments show a growth in average battery size that is similar to the global market trend. With a global trend toward a higher market share of larger vehicle segments, and of SUVs in particular (Global Fuel Economy Initiative, 2023), growth of fleet-wide average battery capacity might be even more pronounced than in the individual segments.

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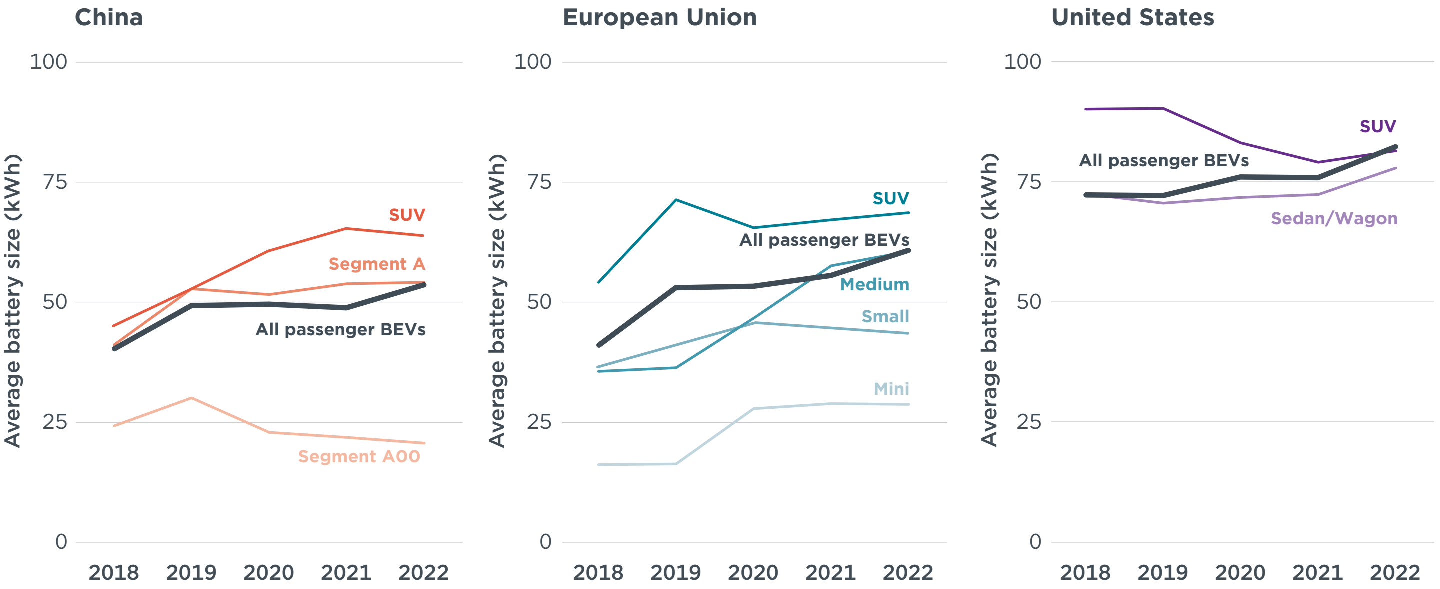
[4] The sales-weighted average battery capacity of light-duty BEVs in Indonesia has fluctuated considerably, from 55 kWh in 2021 to 37 kWh in 2022 to 59 kWh in 2023. This is due to the relatively limited number of BEV models available in the Indonesian market, the lack of models in every LDV segment, and the introduction of certain high-selling models each year. To account for this variability, this study assumed the average battery capacity of Indonesian light-duty BEVs to be 48 kWh, which is the sales-weighted average of all light-duty BEVs sold between 2021 and 2023.

[5] In China, SUVs, A00, and A segment vehicles accounted for 34%, 26%, and 19% of 2022 battery electric passenger vehicle sales, respectively. In the European Union, SUVs, small cars, medium cars, and mini cars accounted for 53%, 13%, 12%, and 11% of 2022 battery electric passenger vehicle sales, respectively. In the United States, SUVs and sedans or wagons accounted for 64% and 29% of 2022 battery electric passenger vehicle sales, respectively.

Figure 5

Trends in average battery capacity of light-duty BEVs sold in China, the European Union, and the United States in segments with the highest BEV sales



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Given the trend of light-duty BEV battery sizes growing over recent years, the Baseline scenario of this study assumes that battery sizes of light-duty BEVs (including light commercial vehicles) will grow by 20% by 2030 (from 2023 levels) in each market except the United States, where they are assumed to increase by only 10% as the average battery capacity in the United States already exceeds that in other regions and has increased more slowly over the last 5 years (Figure *5*). This growth in average battery capacity is underpinned by increases in average vehicle range and a growing share of larger vehicle segments (such as SUVs and pick-ups) among BEV sales. These trends are expected to be partially compensated by an increase in the energy efficiency of BEVs. For example, assuming that per-vehicle energy efficiency improvements and an increasing market share of larger vehicle segments compensate for each other, increasing the battery capacity of an average light-duty BEV in the European Union from 65 kWh to 78 kWh (+20%) would increase the average range by 20% from 433 km to 520 km (Fadhil & Shen, 2024), while increasing the battery capacity of an average light-duty BEV in the United States from 82 kWh to 90 kWh (+10%) would increase the range from 516 km to 568 km.

After 2030, however, the BEV market is expected to reach wider coverage of vehicle segments, and a higher share of cost-optimizing consumers may value vehicle cost savings over further increases in range, halting continued growth in average battery sizes. Therefore, in the long term, energy efficiency improvements could result in a trend towards lower battery capacities. Depending on the state of maturity of the BEV market in specific regions, the assumption of constant battery capacities after 2030 can thus be considered conservative, yielding a higher-end material demand estimate. The average battery size of light-duty BEVs in the five focus regions and globally in 2023 (EV Volumes, 2024) are displayed in Table 1, alongside the assumed values for 2030.

Table 1
Sales-weighted average battery capacity for light-duty BEVs in China, the European Union, India, Indonesia, the United States, and globally, in 2023 and 2030

Market	Average capacity in 2023 (kWh)	Average capacity in 2030 (kWh)	% change
China	56	68	+20%
European Union	65	78	+20%
India	34	41	+20%
Indonesia	59	71	+20%
United States	82	90	+10%
Global	62	75	+20%

In an alternative scenario, this analysis explores how a trend of decreasing light-duty BEV battery capacities until 2030 would impact the overall battery material demand. This scenario assumes that the average battery size of light-duty BEVs decreases by 20% from 2023 to 2030 in all markets and remains constant afterwards. In this case, energy efficiency improvements would be higher than in the Baseline scenario and/or not compensated by an increase in range. Recent ICCT estimates of battery material demand for light-duty BEVs in the United States, for instance, are based on this assumption (Shen et al., 2024).

For light-duty PHEVs, battery capacities are assumed to increase by 20% between 2023 and 2030 and stay constant afterwards. Table A3 in the appendix displays the 2023 sales-weighted average battery sizes for light-duty BEVs and PHEVs globally and in the selected markets (EV Volumes, 2024), as well as assumed 2030 values. This study assumes that the average battery capacity of light-duty BEVs and PHEVs outside of the five focus markets matches the global average battery size.

Heavy-duty vehicles

In 2023, the EU and U.S. heavy-duty vehicle markets had a limited number of battery electric models available, and these corresponded to only a small fraction of total HDV sales. In this early stage of battery electric HDV adoption in these markets, available models are typically smaller, shorter-range trucks and urban transit buses, whose battery sizes might not be representative of the full variety of segments and applications.

For heavy-duty and medium-duty trucks in the European Union and the United States, this study therefore uses battery sizes corresponding to simulated vehicle models with different vehicle load capacities and range requirements. For the European Union, we adopt Basma and Rodríguez's (2023b) estimates of battery capacities for vehicle categories considered in the European Commission's Vehicle Consumption Calculation Tool (VECTO). In this study, the simulated vehicle models from VECTO groups 1–3 are classified as MDTs and those in groups 4–16 are considered HDTs. The battery capacities of these vehicle models are weighted by the current and projected sales shares of these types of vehicles within the MDT and HDT segments, as provided by Basma and Rodríguez. For future vehicles within each segment, changes in battery capacity due to energy efficiency improvements are considered; chassis light-weighting, increased battery energy density, and improved road load technologies are expected to decrease the required battery capacity for MDT and HDT applications by 16%–40% from 2022 to 2030 (Basma and Rodríguez, 2023b). For MDTs, however, this is overcompensated by a projected increase in the sales share of larger electric applications requiring heavier vehicles and longer ranges, resulting in a projected increase in the average battery capacity of MDTs in the European Union by

29% between 2023 and 2030. Even growth in sales shares within the HDT segment, in contrast, maintains an assumed 25% reduction in the average battery capacity.

For the United States, we adopt Slowik et al.'s (2023) estimates of the battery capacities of electric class 4–7 trucks, which are grouped as MDTs in this study, and class 8 trucks, tractor trucks, and refuse trucks, grouped as HDTs. These are weighted by the projected sales shares of BEVs (and FCEVs) in the different MDT and HDT classes as provided by Ragon et al. (2023). Slowik et al. (2023) expect future energy efficiency improvements in trucks and buses to contribute to reductions in battery capacity of between 1% and 14% depending on the segment. Still, based on Ragon et al.'s projections of growing sales shares of electric short- and long-haul tractor-trailers, the average HDT battery size is projected to increase by 7% between 2023 and 2030. For MDTs, even sales shares of different segments result in a reduction in the average MDT battery size by 5% between 2023 and 2030.

For China, where the battery electric HDV market is comparatively more mature, this study assumes that the models currently available are representative of the full range of vehicle segments and applications today and calculates average battery sizes for MDTs and HDTs based on market data (Gasgoo, 2023). The vehicle models are grouped into segments based on the weight classes used in the ICCT Roadmap model: MDTs are trucks with a GWV between 3.5 and 15 tonnes and HDTs are trucks with a GVW above 15 tonnes. The average battery sizes for MDTs and HDTs in 2023 are 139 kWh and 326 kWh, respectively. This analysis assumes that the Chinese MDT and HDT markets will evolve similarly to the EU and U.S. markets, and therefore uses the simple average of the simulated battery size values for these markets for China, resulting in assumed battery capacities of 161 kWh for MDTs (+16%) and 564 kWh for HDTs (+73%) in 2030.

For India, the average battery capacities of MDTs and HDTs are based on simulations of battery electric trucks corresponding to comparable ICE trucks in use in India today (Kaur et al., 2024). We assume an average battery capacity of 113 kWh for MDTs (corresponding to Kaur et al.'s results for electric trucks with a GVW below 12 tonnes) and a battery capacity of 236 kWh for HDTs (corresponding to their results for trucks over 12 tonnes). The development of battery sizes in India through 2030 is assumed to match the energy efficiency improvements of comparable segments in the European Union and the United States, without considering the impact of the development of sales shares of different subsegments in those markets. This analysis thus assumes the average battery sizes of battery electric MDTs and HDTs in India decrease by 13% and 19%, respectively, between 2023 and 2030.

For MDTs and HDTs in all other regions, including Indonesia, this study assumes 2023 battery sizes are equivalent to the average battery size for each segment in China. In 2030, we assume that with energy efficiency improvements and shifting subsegment sales shares, the battery capacities evolve to match the simple mean of the battery sizes in the United States and the European Union.

For buses, this study assumes that the 2023 sales-weighted average battery capacity of buses in China, of 213 kWh (Gasgoo, 2023), is representative of a developed battery electric bus market with all types of urban transit and long-distance coach buses. This is the value assumed for China, India, Indonesia, and the overall global market in 2023 and is held constant through 2030. For the EU and U.S. markets, this study assumes an average battery size of 250 kWh in 2023 that decreases to 223 kWh (-11%) by 2030, based on simulations for U.S. buses by Slowik et. al. (2023) weighted by U.S. sales projections from Ragon et al. (2023).

The average battery sizes for MDTs, HDTs, and buses for the focus regions and globally in 2023 and 2030 are detailed in Table *2*. HDV battery sizes are assumed to stay constant after 2030.

Table 2

Sales-weighted average battery capacity by HDV segment in China, the European Union, India, Indonesia, the United States, and globally, in 2023 and 2030

Market	Segment	Average capacity in 2023 (kWh)	Average capacity in 2030 (kWh)	% change
China	**MDT**	139	161	+16%
	HDT	326	564	+73%
	Bus	213	213	0%
European Union	**MDT**	132	170	+29%
	HDT	724	545	-25%
	Bus	250	223	-11%
India	**MDT**	113	100	-13%
	HDT	236	190	-19%
	Bus	213	213	0%
Indonesia	**MDT**	139	161	+16%
	HDT	326	564	+73%
	Bus	213	213	0%
United States	**MDT**	160	152	-5%
	HDT	546	583	+7%
	Bus	250	223	-11%
Global	**MDT**	139	161	+16
	HDT	326	564	+73%
	Bus	213	213	0%

Two- and three-wheelers

In markets with high two- and three-wheeler sales, two-wheelers comprise almost the entirety of the combined sales of these vehicles across all power train types, accounting for 96% of two- and three-wheeler sales in India in 2023 (Society of Indian Automobile Manufactures, 2024) and over 99% of such sales in Indonesia, the Philippines, and Thailand in 2020 (Le & Yang, 2022). For this reason, the average battery capacity of two- and three-wheelers is assumed to be similar to the battery capacity of two-wheelers alone. In India, typical battery capacities of electric scooters and motorcycles vary between 2.2 kWh and 4.6 kWh, depending on the vehicle category, while electric rickshaws and other three-wheelers show typical values of 3.7 kWh and 7.4 kWh, respectively (Gode et al., 2021). For two-wheelers in Vietnam, the capacities vary between 1.2 kWh and 2.3 kWh, with 1.3 kWh models being most popular (Tran et al., 2022). In Indonesia, the most popular electric two-wheeler model has a battery capacity of 1.4 kWh (Mera & Bieker, 2023). A recent United Nations Environment Programme (2024) report identified average battery capacities in Asia of 2.1 kWh for scooters and 3.5 kWh for motorcycles.

Based on these values, this analysis assumes the 2023 average battery capacity for both two- and three-wheelers to be 3.0 kWh for all markets. This is considered a conservative estimate for countries like Indonesia. We assume a rate of growth for two- and three-wheeler battery sizes equivalent to that of LDVs: a 20% increase in capacity from 2023 levels by 2030. Battery sizes are assumed to stay constant after 2030.

Battery replacement

Lithium-ion batteries are typically considered to reach the end of their useful life when they reach 70%–80% of their initial capacity. In rigid battery durability tests, NMC batteries have been demonstrated to sustain more than 80% of their initial capacity even after 3,000–5,000 equivalent full cycles (Harlow et al., 2019; Schmalstieg et al., 2014). LFP batteries have been shown to remain above that value even after 5,000–6,000 equivalent full cycles (Naumann et al., 2020; Spingler et al., 2020). For light-duty BEVs with a range of 200–400 km, a battery lifetime of 3,000–5,000 equivalent full cycles would correspond to a mileage of 600,000–2,000,000 km. This is several times higher than an average LDV lifetime mileage of 150,000–300,000 km (Bieker, 2021a). Similarly, the battery of electric two-wheelers with a range of 40–50 km could sustain for 120,000–250,000 km, which again exceeds an assumed 100,000 km lifetime mileage of these vehicles (Mera & Bieker, 2023). For battery-electric HDVs with a range of 200–600 km, the battery lifetime would correspond to a mileage of 600,000–3,000,000 km, which—depending on the segment and application—is also higher than or sufficient for operation over the vehicle lifetime. The study thus assumes that no battery replacement will be needed for any of the vehicle segments considered.

STEP 3: MARKET SHARES OF BATTERY TECHNOLOGIES

Baseline scenario

To determine market shares of battery technologies, the Baseline scenario only considers those technologies that are available on the mass market today. The impact of potential future large-scale commercialization of sodium-ion batteries, lithium manganese iron phosphate cathode-based lithium-ion batteries, or lithium metal anode-based solid-state batteries, for instance, are not considered in this scenario.

At the cathode, the lithium-ion battery market for BEVs and PHEVs in all vehicle segments is mainly split between three types of materials: NMC, LFP, and NCA. On a global level, the market shares of cathode materials in terms of battery capacity installed in vehicles in 2023 were 51% (NMC), 41% (LFP), and 7% (NCA) (BMI, 2024b). Relative sales shares of these materials differ between markets and segments. For LDVs in China, for instance, the share of LFP batteries in terms of battery capacity installed in vehicles increased from 10% in 2020 to about 50% in 2023 (EV Volumes, 2024). Data from EV100 (2024) and ZEDATA (2024) indicate an even higher share of LFP cathodes in the Chinese LDV market, of 14% in 2020 and 60% in 2022. In India, the evolving light-duty BEV and PHEV market shows a comparatively high share of LFP batteries, accounting for 61% of vehicular battery capacity in 2022 and 46% in 2023 (EV Volumes, 2024). In contrast, shares of LFP batteries in the EU and U.S. LDV markets are comparatively low, at 1% (European Union) and 0% (United States) in 2022 and 4% (European Union) and 7% (United States) in 2023. For HDVs in China, the share of LFP cathodes was as high as 99% in 2021 (Mao et al., 2023). In the European Union, in contrast, LFP and NMC batteries accounted for an estimated one-third and two-thirds of the 2023 HDV market, respectively (Mulholland et al., 2024).

Given this variation, assuming the same global average shares of battery technologies for each market might underestimate the demand for nickel, cobalt, and manganese in markets with above-average NMC shares and overestimate the demand in markets with higher shares of LFP batteries. To better reflect market conditions, this analysis therefore divides the global battery market into two groups: an NMC-leaning group and an LFP-leaning group.[6]

NMC batteries have higher specific energy than LFP batteries, but they are also more expensive on a per-kWh basis. Markets with higher-than-average shares of NMC batteries (e.g., the United States, the European Union, Japan, and South Korea) generally have higher per-capita gross domestic product (GDP). Economic relations are also close among many of the countries in this group, including in the form of free trade agreements. As a result, we assume that future market shares of battery technologies in other markets with high per-capita GDP or close economic ties to NMC-leaning countries (e.g., Australia, Canada, and Mexico) will develop in the same way as projected for the European Union, the United States, Japan, and South Korea. On the other hand, we assume that countries with relatively low GDP per capita, including India and Indonesia, and countries in Central and South America, Africa, and the Asia–Pacific region (other than Japan and South Korea) will develop LFP shares above the global average, following current market shares and projections for China.

In the Baseline scenario, the development of cathode material market shares at the global level is based on estimates by BMI (2024b) and the IEA (2022). To translate these values into market shares for the NMC- and LFP-leaning groups, we considered market-specific estimates by Transport & Environment (2023) for the European Union, by Buchert et al. (2023) for Germany, and by Shen et al. (2024) for the United States. For each group of countries, battery technology shares correspond to the accumulated demand for LDVs, HDVs, and two- and three-wheelers. Moreover, shares of battery capacity demand within these segments (e.g., a higher share of LFP batteries for HDVs than for LDVs) were also taken into account. The projected battery technology shares for the NMC-leaning and LFP-leaning groups are displayed in Figure 6. In both groups, the two main trends observed today are assumed to continue: the growth of the share of LFP batteries and, within NMC battery variants, a shift towards low cobalt, high nickel materials (e.g., from NMC111 to NMC811 and NMC955). Figure 7 displays the global market shares, and thus the battery capacity-weighted average shares, of the NMC- and LFP-leaning groups of countries.

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[6] The NMC-leaning group includes the European Union, the United States, the United Kingdom, Australia, Canada, Japan, Mexico, South Korea, and eastern European countries. The LFP-leaning group includes China, India, Indonesia, Africa, Brazil, the Middle East, Asia–Pacific countries (excluding Japan and South Korea), Russia, and Latin America (excluding Mexico).

Figure 6

Projected shares of battery technologies in the BEV and PHEV market in the NMC-leaning (top) and the LFP-leaning (bottom) groups of countries in the Baseline scenario

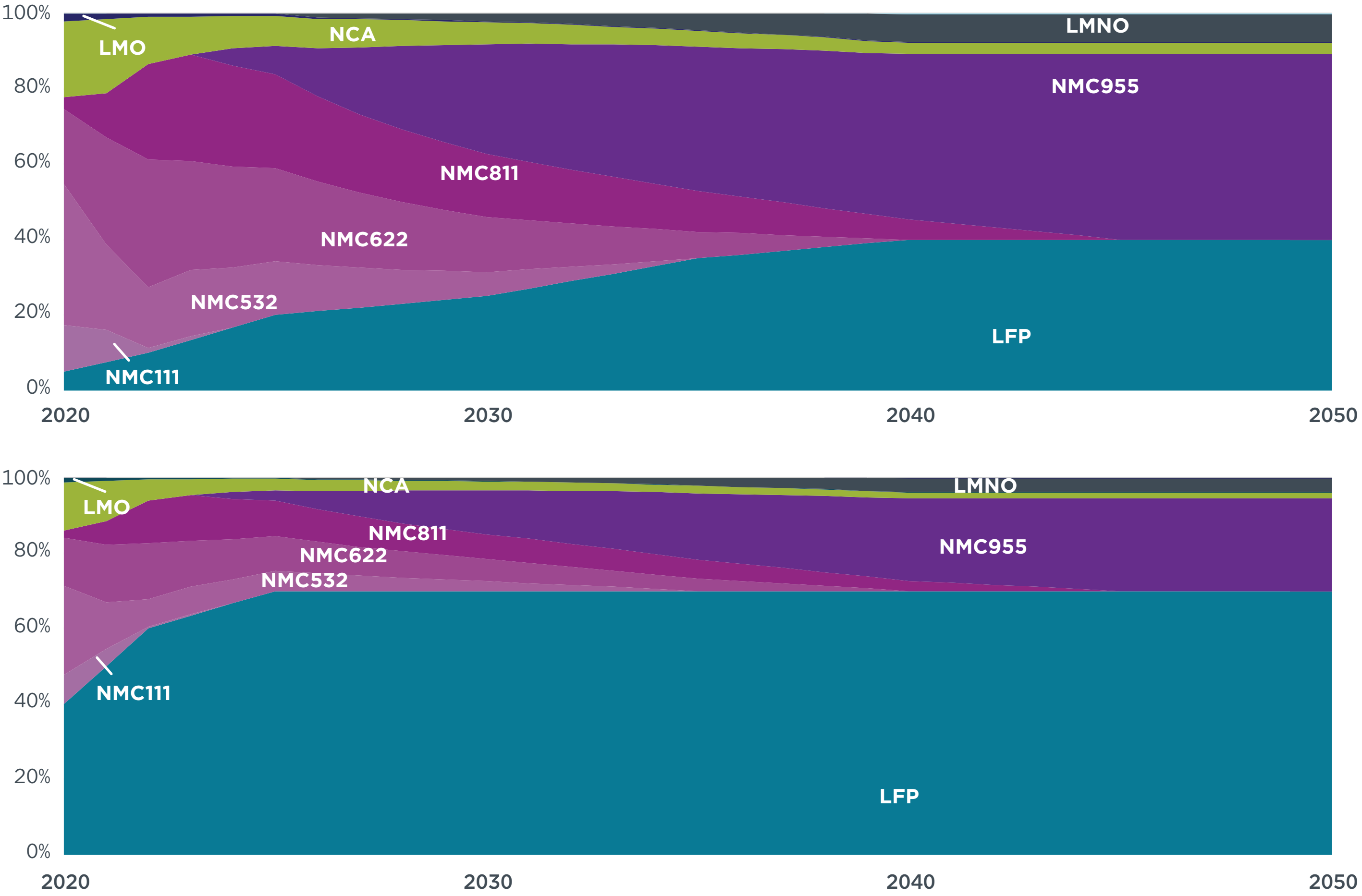

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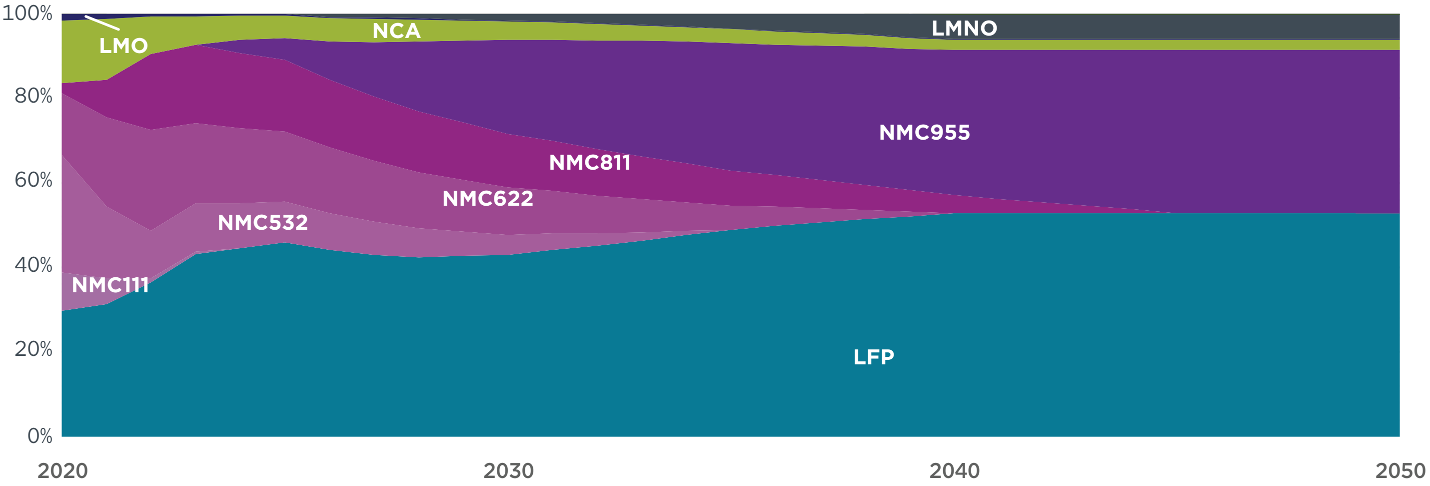
Figure 7

Projected shares of battery technologies in the global average BEV and PHEV market in the Baseline scenario



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At the anode, two types of materials dominate the current BEV and PHEV battery market: graphite anodes and graphite-silicon composite anodes. In graphite-silicon composite anodes, a certain share of graphite is replaced by silicon. Bloomberg New Energy Finance (BNEF; BNEF, 2023) estimates that in 2023, about 30% of batteries used in electric vehicles had graphite-silicon composite anodes, most with a silicon weight share of 5%–10%. For the future development of the market, it is expected that both the share of batteries using graphite-silicon composite anodes and the share of silicon used in these composites will increase. Based on BNEF projections, this analysis assumes that until 2040, the share of anodes using graphite-silicon composites increases to 70%, with a silicon weight share of 15%–20% (BNEF, 2023). For the overall market average, including silicon-containing and non-silicon-containing anodes, the weight share of silicon to graphite would thereby increase from 2% in 2023 to 10% in 2040, after which it remains constant. These trends are assumed for all markets.

In the major two- and three-wheeler markets today, lead-acid batteries make up a large proportion of the battery electric two- and three-wheelers on the road. In China, for instance, 25% of two- and three-wheelers sold in 2022 had lithium-ion batteries, and nearly all the rest used lead-acid batteries (iResearch, 2023). In 2020, 68% of two-wheelers in Indonesia, Vietnam, Thailand, and the Philippines (Le & Yang, 2022) and between 45% and 98% of electric rickshaws in India were estimated to use lead-acid batteries *(UNEP, 2024).* Looking ahead, however, lithium-ion and sodium-ion batteries are expected to gain market share in two- and three-wheeler fleets as their production costs decline. Given the current prevalence of lead-acid batteries in large two- and three-wheeler markets, this analysis assumes that 30% of all battery electric two- and three-wheelers use lithium-ion batteries in 2023, a proportion that is assumed to increase linearly to 100% in 2035.

High LFP Share scenario

In an alternative scenario, the analysis assesses how the projected demand in battery materials would change if the current trend of increasing market shares of LFP batteries in both the NMC-leaning and the LFP-leaning groups of countries were more pronounced than in the Baseline scenario. This High LFP Share scenario assumes that the LFP share in NMC-leaning markets rises to 45% in 2030 compared to 25% in the Baseline. In LFP-leaning markets, the LFP share rises to 85% in 2030, compared to 70% in the Baseline. In both groups, the LFP share rises linearly from the assumed level in 2024 in the Baseline scenario and remains constant after 2030. The shares of non-LFP cathodes evolve in proportion to their assumed evolution in the Baseline scenario. Figure A1 in the appendix displays the development of the shares of cathode materials for the NMC- and LFP-leaning groups and of global battery technology market shares in the High LFP Share scenario.

High Sodium-Ion Battery Share scenario

This analysis also explores how the projected demand for battery materials would be impacted if substantial shares of BEVs and PHEVs sold globally were powered by sodium-ion instead of lithium-ion batteries. Sodium-ion batteries are expected to be cheaper, but offer a lower specific energy, than lithium-ion batteries–comparable to the benefits and drawbacks of using LFP batteries relative to NMC counterparts. It is thus expected that sodium-ion batteries would compete with and replace market shares of LFP batteries while not affecting the sales shares of NMC batteries in market segments with high cost and higher specific energy demand. The High Sodium-Ion Battery Share scenario builds on the High LFP Share scenario and assumes that by 2030, sodium-ion batteries displace a quarter of the LFP share in that scenario to reach a market share of 11% in NMC-leaning countries and 21% in LFP-leaning countries, corresponding to a 15% global market share. Sodium-ion batteries are assumed to phase in linearly from 0% in 2024. The combined shares of non-LFP and sodium-ion batteries are the same as in the High LFP Share scenario. Figure A2 in the appendix displays the development of lithium-ion and sodium-ion battery market shares in the High Sodium-Ion Battery Share scenario for the NMC- and the LFP-leaning groups and globally.

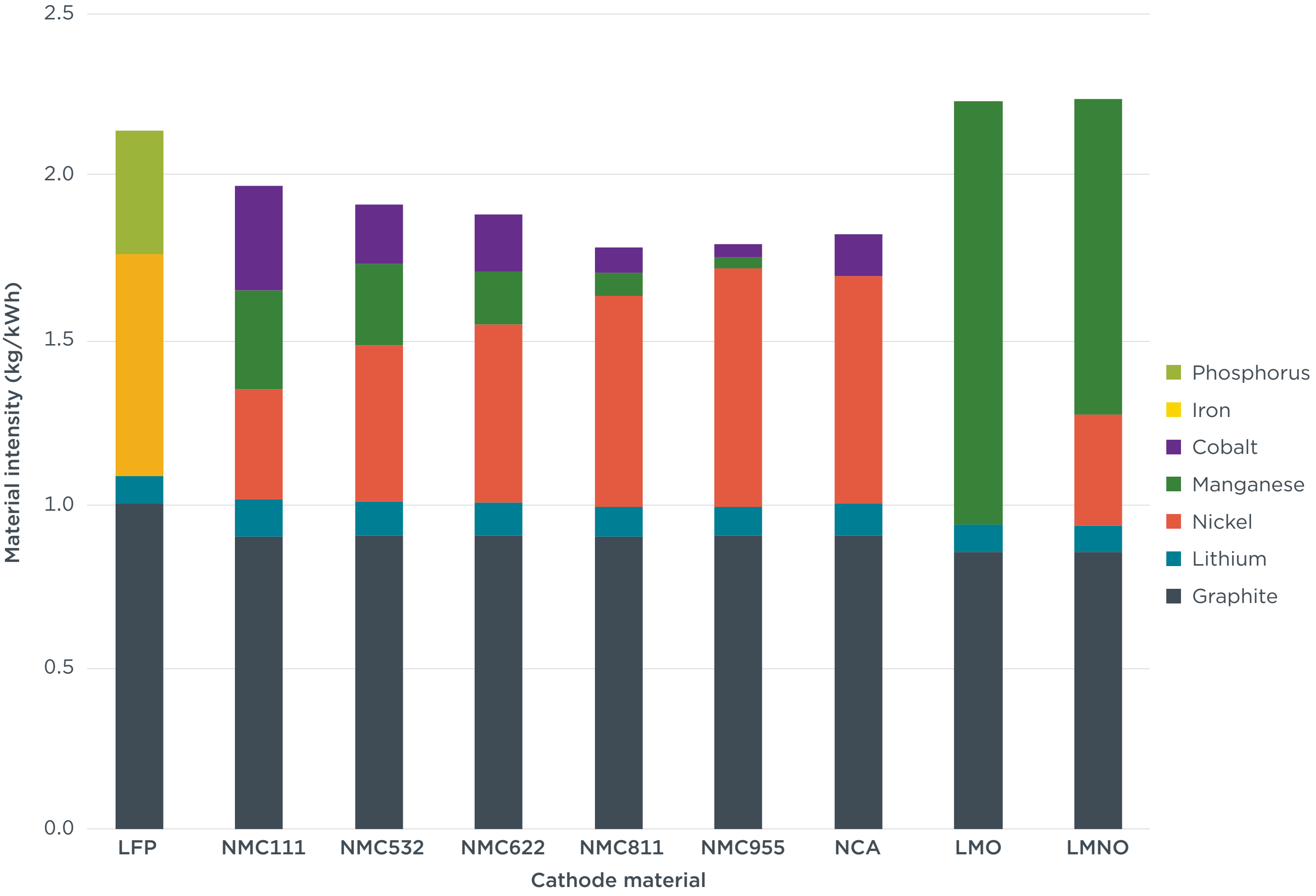
BMI (2023a) estimates that layered oxide cathodes make up 76% of the announced sodium-ion battery production capacity in 2030. This analysis assumes auto manufacturers will use layered oxide cathodes in sodium-ion batteries due to their higher energy densities compared to sodium-ion batteries with polyanionic or Prussian Blue cathodes.

STEP 4: BATTERY MATERIAL INTENSITY

This study employs material intensity data in kilograms per kilowatt-hour of battery capacity from the Argonne National Laboratory's 2022 Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model (Argonne National Laboratory, n.d.). Additional values are calculated for anode and cathode materials not included in the GREET model, including lithium manganese nickel oxide (LMNO) cathodes and graphite-silicon composite anodes. The material intensity of the different cathode and anode materials for lithium-ion batteries are presented in Table A4 in the appendix. Figure 8 illustrates the demand for selected materials at the cathode and anode for lithium-ion batteries with graphite anodes (i.e., without silicon). As presented in Table A4, a significant share of the graphite in lithium-ion battery anodes is assumed to be replaced by silicon in the future.

Figure 8

Material intensity for different lithium-ion battery technologies



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For sodium-ion batteries, this analysis considers a hard carbon anode (i.e., not graphite) combined with a layered oxide cathode, as this type of cathode makes up the majority of planned capacities for sodium-ion battery production (BMI, 2023a). While several variants of layered oxide cathodes are being discussed (Zuo et al., 2023), this study considers sodium nickel manganese magnesium titanium oxide (Wood Mackenzie, 2023). With a weight of cathode active material $Na_{0.833}[Ni_{0.317}Mn_{0.467}Mg_{0.1}Ti_{0.117}]O_2$ of 2.5 kg/kWh, the material demand at the cathode per kilowatt-hour of battery capacity corresponds to 0.5 kg of sodium, 0.4 kg of nickel, 0.6 kg of manganese, 0.1 kg of magnesium, and 0.1 kg of titanium.

On top of the material eventually used in the cathode and anode of the battery cells, this analysis considers the additional material demand from losses during battery production. The assumed rates of production scrap are based on rates reported in the literature (Circular Energy Storage, 2022; Gaines et al., 2023). Production yield rates are expected to improve due to maturing production processes, consolidation of battery manufacturers, and automation. The production scrap rate for all materials is assumed to be 5% between 2023 and 2026, 4% between 2027 and 2030, and 3% in 2031 and beyond. On the other hand, this analysis does not consider the potential demand stemming from losses in mineral refining processes.

STEP 5: BATTERY RECYCLING

Baseline scenario

In the Baseline scenario, this study accounts for the recovery of materials from battery recycling only to the extent currently mandated with element-specific recovery rates. As of 2023, the EU Battery Regulation was the only policy to mandate minimum recovery rates for different raw materials. These rates are 50% of lithium and 90% of nickel and cobalt between 2027 and 2031, increasing to 80% of lithium and 95% of nickel and cobalt starting in 2032. There are no specified recovery rates for graphite or manganese, which this analysis thus assumes are not recovered (The European Parliament, 2023; Tankou et al., 2023a). Given the nascent state of electric vehicle battery recycling, there is little real-world data on rates of battery collection and second-life reuse, and thus a high level of uncertainty associated with assuming these values. This analysis assumes 90% of BEV and PHEV batteries are collected and that 50% of collected batteries are reused in a second-life application. The collection rate is based on the assumption that a proportion of vehicles reach their end of life in countries with less developed battery collection and recycling infrastructure. The reuse rate is an uncertain assumption that balances the likelihood of vehicle batteries being suitable for second-life applications at their end of life against the possible economic incentives favoring the recovery of their constituent materials and their reuse in new batteries. Second-life applications are assumed to last for 10 years, after which the batteries enter the recycling stream. Battery reuse delays the recovery of materials for new batteries, so the assumption that 50% of batteries will be reused results in a conservatively low secondary material supply.

Global Recycling scenario

An alternative scenario assumes that all countries globally adopt recycling mandates as stringent as those in the EU's Battery Regulation on the same timeline.

GLOBAL RESULTS

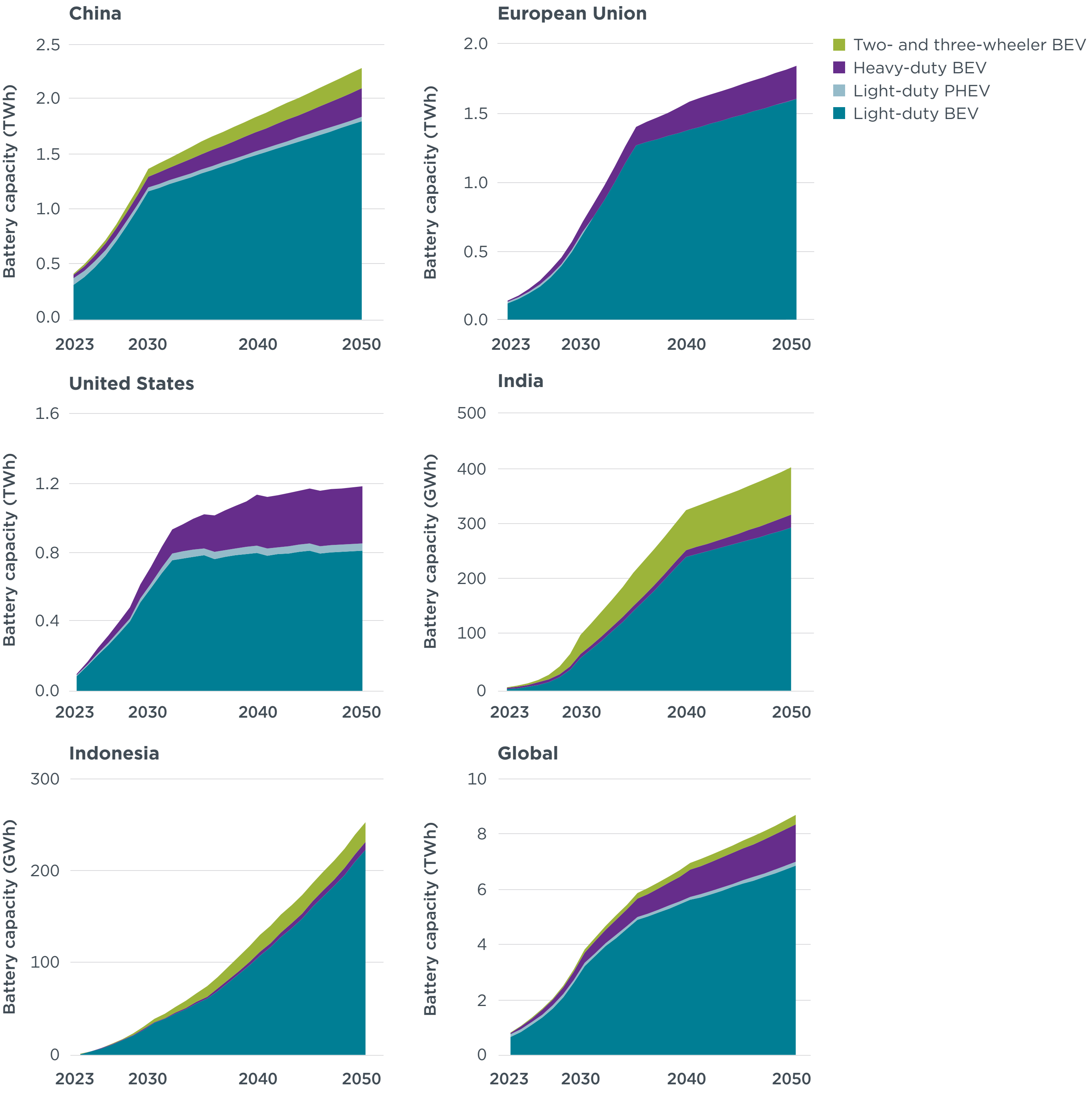
BATTERY DEMAND AND CELL PRODUCTION

As presented in Figure 9, the Baseline scenario projects that the annual global battery demand for BEVs and PHEVs across the two- and three-wheeler, LDV, and HDV segments increases from 808 GWh in 2023 to 3.8 TWh in 2030, 7.0 TWh in 2040, and 8.7 TWh in 2050. Battery demand for LDVs alone increases by a factor of 11 between 2023 and 2050, mainly due to a 9-times increase in annual light-duty BEV sales. The battery demand for HDVs is projected to grow by a factor of 24 between 2023 and 2050. For two- and three-wheelers, the annual battery capacity demand is projected to increase by a factor of 22 in the same timeframe, as annual sales of two- and three-wheeler BEVs with lithium-ion batteries are expected to grow by a factor of 19 between 2023 and 2050.

Projected annual battery demand by market, also pictured in Figure 9, roughly correlates with each market's BEV and PHEV sales in the LDV and HDV segments. By contrast, sales of two-and three-wheelers, given their comparatively small battery capacities, have a minor impact on a market's battery demand. China's share of global battery demand is projected to decrease from 60% in 2023 to 21% in 2050 as other markets catch up in BEV and PHEV sales shares. Details on projected battery capacity demand in China, the European Union, the United States, India, and Indonesia, are presented in market-specific results sections below.

Figure 9

Annual BEV and PHEV battery demand in the Baseline scenario, by market and vehicle segments



Note: Demand projection excludes lead-acid batteries.

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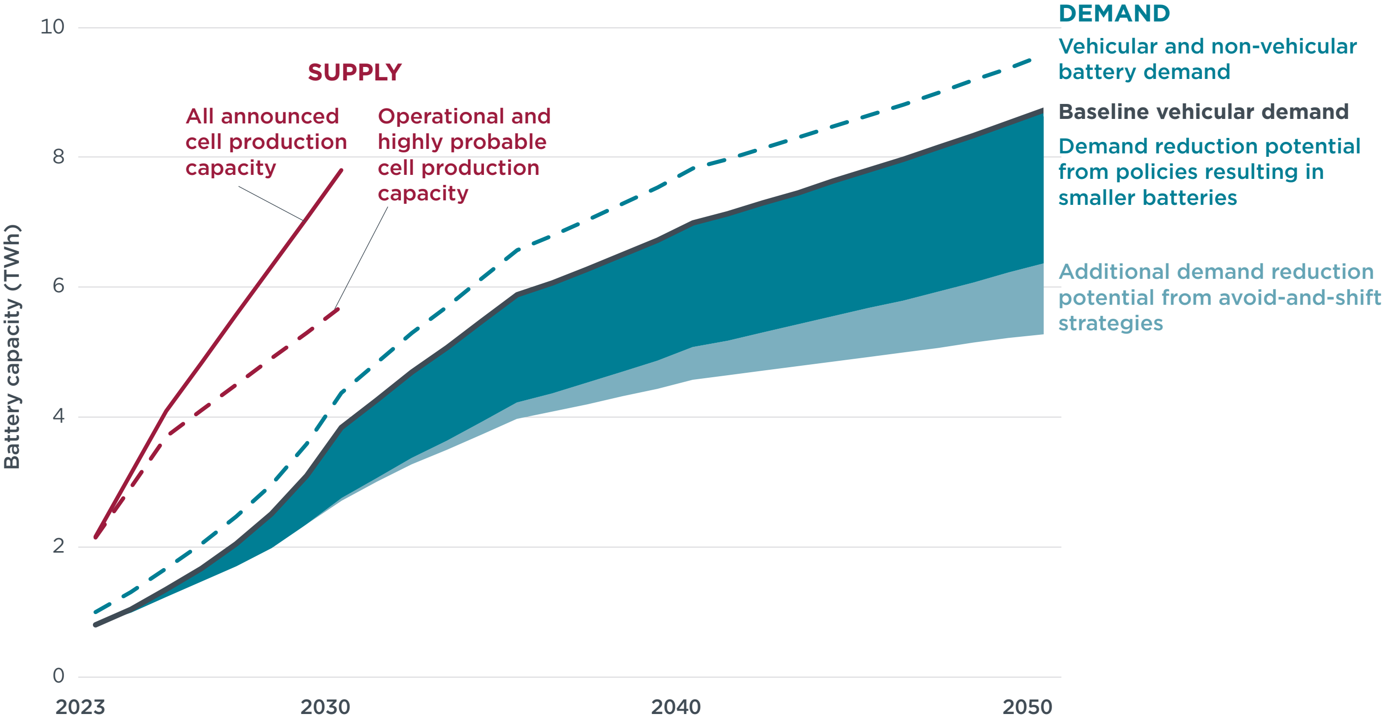
Figure 10 examines how global battery capacity demand in the Baseline scenario could be reduced by incentivizing smaller batteries in light-duty BEVs and lowering vehicle demand through avoid-and-shift policies. While the Baseline scenario assumes that average battery capacity in the LDV and two- and three-wheeler segments will keep increasing until 2030, the Smaller Batteries scenario assumes that the average battery capacity of light-duty BEVs would decrease by 20% in the same period. For light-duty PHEVs and HDVs, no change in average battery capacities is considered. Reducing LDV battery capacities lowers aggregate annual battery demand by 28% in 2030 and 27% in 2040 compared with the Baseline scenario.

Additionally, if private passenger car and freight transport are partly avoided and shifted to different modes of transport, as presented in the Avoid-and-Shift scenario, global battery demand is reduced by an additional 10% in 2040 and 17% in 2050. As avoid-and-shift strategies are expected to take time to be effective, the short-term reduction in battery capacity demand is comparatively low, at only 1% in 2030.

Figure 10

Annual global battery demand by demand reduction scenario compared with announced cell production capacity



Note: This demand projection excludes lead-acid batteries.

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Comparison with announced cell production

On the supply side, Figure 10 also displays the expected development of global cell production capacities until 2030 based on announcements up to July 2024 (BMI, 2024a). The figure distinguishes between the total announced cell production capacities on one hand, and only those that either correspond to plants that are already operational or to plants that are under construction and are considered by BMI to be “highly probable” to meet the announced future capacities on the other hand. The total announced cell production capacities include also those plants that are not yet under construction and those BMI considers as “probable” or “possible” to meet the announced capacities. All production capacities are corrected by an 85% utilization factor.

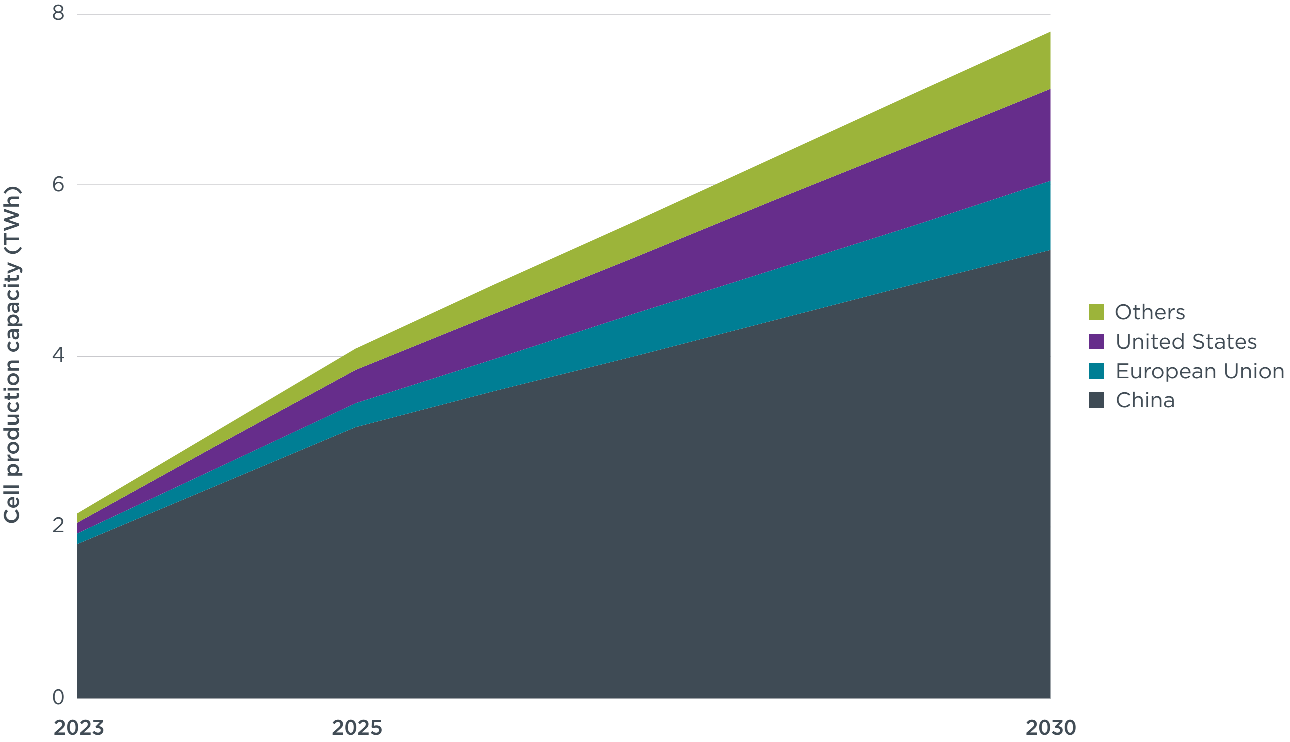
In 2023, vehicles made up 80% of global lithium-ion battery demand, followed by stationary energy storage systems (13%) and portable electronics (7%; BMI, 2024b). Demand for energy storage systems is expected to increase at a similar rate as for BEV and PHEV batteries, from 123 GWh in 2023 to 447 GWh in 2030 and 730 GWh in 2040 (BMI, 2024b). In contrast, demand for portable electronics is projected to grow at a much slower constant rate—from 66 GWh in 2023 to 112 GWh in 2040—and diminish in relative importance.

Comparing global battery demand projections for vehicle and non-vehicle applications to operational and highly probable battery cell production capacities in 2030, the announced cell supply exceeds Baseline scenario demand by a large margin. Indeed, on a global level, announced cell production capacities in 2030 are almost twice as high as the projected demand. By market, current and announced future battery cell production capacities are primarily concentrated in China, with the United States and European Union expected to become the second and third largest battery producing markets by 2030. The geographic distribution of announced cell production capacities is illustrated in Figure 11, based on data from BMI (2024a). Figure 12 further illustrates the geography of cell production, highlighting total capacities announced for 2023 and 2030 (not distinguishing by likelihood of realization).

Between 2023 and 2030, alongside a fourfold increase in cell production capacity globally, the share of global battery cell production occurring in China is projected to decrease from 84% to 67% while the share occurring in the European Union grows from 6% to 10% and the proportion in the United States grows from 6% to 14%. Growth outside these major vehicle markets is distributed across different countries, as shown in Figure 12. Although international battery production companies were operational in Japan and South Korea in 2023, with announced production capacities of 35 GWh and 46 GWh, respectively, the battery production capacity in these countries is projected to increase at a slower pace between 2023 and 2030 (by a factor of 2 in both regions, compared to a factor of 9 in the United States).

Figure 11

Announced battery cell production capacity by market



Note: Data, sourced from BMI (2024a), exclude lead-acid battery production.

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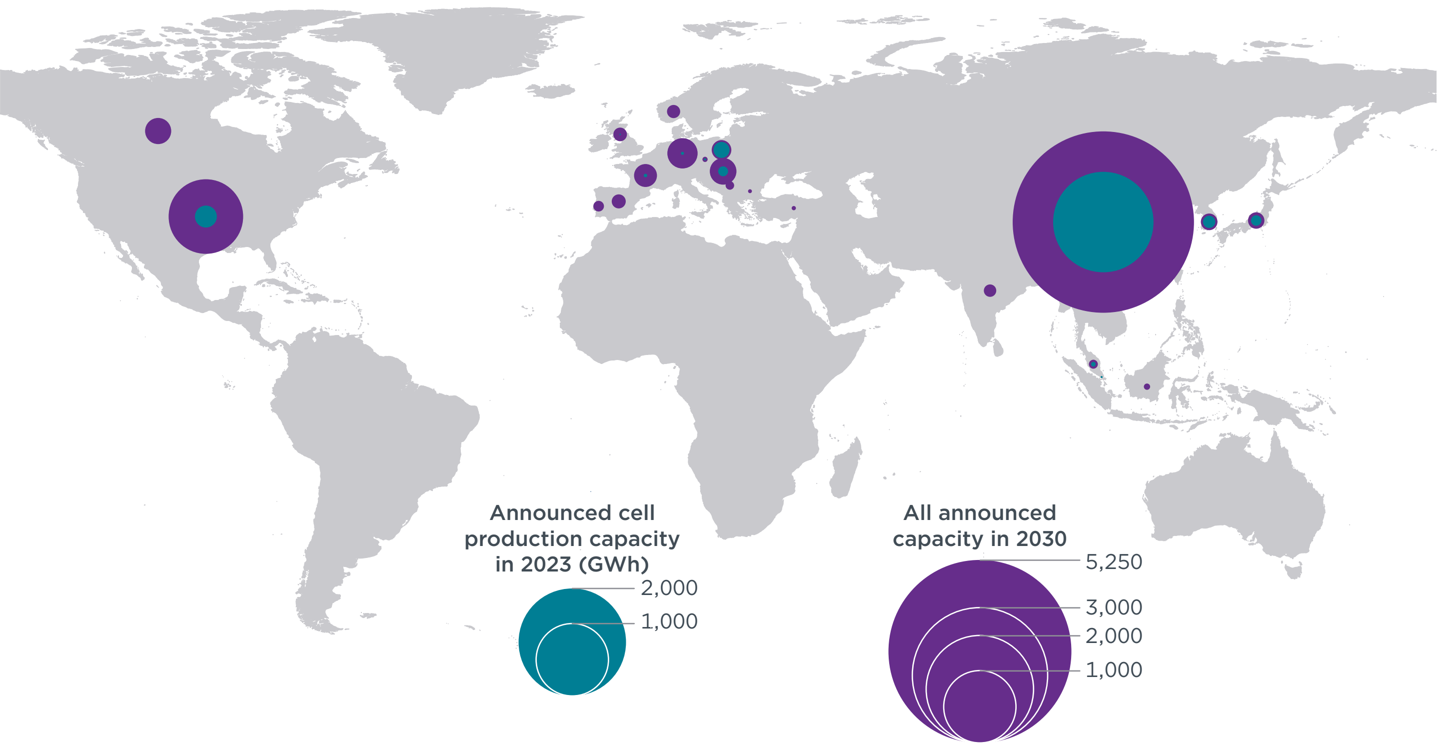
Figure 12

Announced battery cell production capacity in 2023 and 2030 by country



Note: Data, sourced from BMI (2024a), include production capacity for all applications and exclude lead-acid battery production.

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BATTERY MATERIAL DEMAND AND SUPPLY

The different variants of cathodes for lithium-ion batteries require different types and amounts of materials. Among the minerals of focus in this study, NMC cathodes require lithium, nickel, manganese, and cobalt; NCA cathodes require lithium, nickel, and cobalt; and LFP cathodes require only lithium. All types of lithium-ion batteries require graphite at the anode. Sodium-ion batteries, in contrast, may require some nickel and manganese, but no lithium or graphite. Translating the demand for battery capacity into demand for materials needed to produce these batteries is thus dependent on the assumed market shares of battery technologies. These shares can be projected with some level of certainty in the near term, assuming current market trends persist, but the longer-term outlook (e.g., for 2040 or 2050) is highly uncertain. To account for this uncertainty, as noted above, this study presents three scenarios for the future development of the battery technology market shares:

1. The Baseline scenario assumes that the share of LFP batteries will continue to moderately increase.
2. The High LFP Share scenario considers stronger growth in LFP battery market shares.
3. The High Sodium-Ion Battery Share scenario considers that a substantial share of demand would be met with sodium-ion batteries.

Figure 13 presents the projected annual demand for lithium, nickel, cobalt, and graphite in the three battery technology mix scenarios. Projected demand for manganese in these scenarios is illustrated in Figure A3.

For lithium, the Baseline scenario shows a rapid increase in annual demand to 359 kt in 2030 and a continued but slower increase to 622 kt in 2040. The High LFP Share scenario does not differ substantially from the Baseline: As we assume LFP batteries require 0.08 kg lithium per kWh of battery capacity and NMC batteries require 0.09–0.10 kg of lithium, the higher share of LFP reduces the annual demand for lithium by 2% in 2030 and 1% in 2040. In contrast, as shown by the dotted line, the High Sodium-Ion Battery Share scenario shows a large reduction in demand for lithium relative to the Baseline, of 17% in 2030 and 16% in 2040.

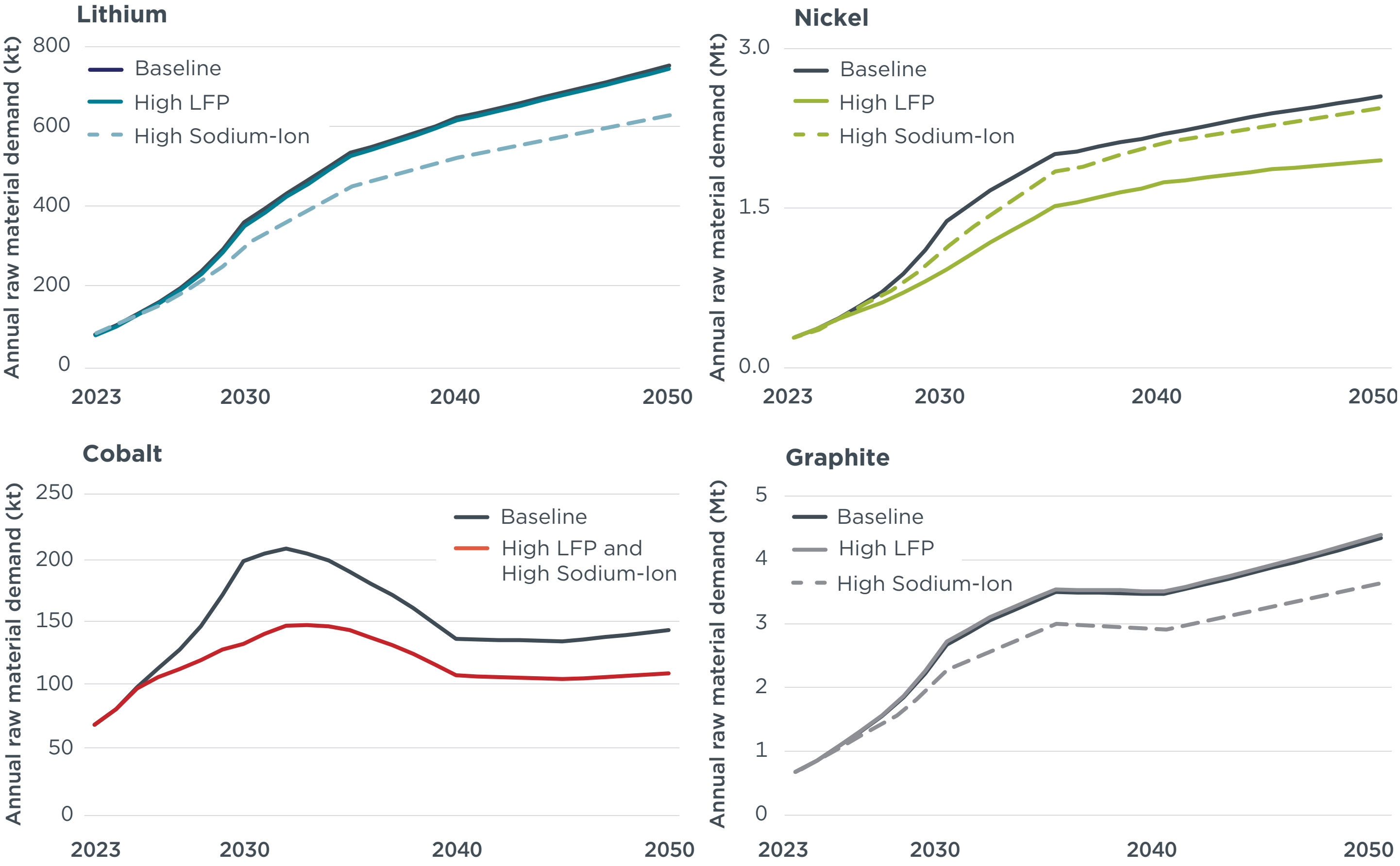
In the Baseline, the demand for nickel increases at a similar pace as for lithium, growing quickly to 1.4 Mt in 2030 and at a slower rate to 2.2 Mt in 2040. It is impacted by two opposing trends: a shift to higher-nickel NMC cathodes within the family of NMC cathodes and a decreasing share of NMC cathodes overall. The demand for cobalt, in contrast, is reduced by both of these trends. For that reason, annual demand in cobalt is expected to increase to 197 kt in 2030, peak in 2032, fall to 136 kt by 2040, and continue to decline through 2050. In the High LFP Share scenario, demand for nickel and cobalt, which are needed in NMC cathodes but not in LFP cathodes, is significantly lower, with reductions of 33% in 2030 and 21% in 2040 relative to the Baseline. In the High Sodium-Ion Battery Share scenario, meanwhile, annual demand for cobalt is the same as in the High LFP Share scenario, because sodium-ion batteries are assumed to replace LFP batteries and the sodium-ion battery type assessed in this study does not contain cobalt. For nickel, annual demand in the High Sodium-Ion Battery Share scenario is only slightly lower than in the Baseline scenario, as this type of sodium-ion battery contains 0.45 kg nickel per kWh, compared to 0.52 kg for NMC622 and 0.82 kg for NMC911, and partly replaces market shares of non-nickel containing LFP cathodes.

For manganese, displayed in Figure A3, the shift towards higher-nickel NMC cathodes within the family of NMC cathodes and the decrease in the market shares of NMC overall would result in a pattern similar to that observed for cobalt. Due to the assumed growth of LMNO battery market shares, however, the demand in manganese is projected to increase to 243 kt in 2030 and 526 Mt in 2040. Like nickel and cobalt, manganese demand declines with higher LFP uptake but increases significantly with sodium-ion battery uptake. Sodium-ion batteries are expected to contain more manganese per kilowatt hour than all NMC variants, but less than LMO or LMNO batteries.

Graphite demand increases rapidly to 2.7 Mt in 2030 before flatlining in the second half of the 2030s due to assumed increasing proportions of silicon in anodes, arriving at 3.5 Mt in 2040. After 2040, the proportion of added silicon in anodes stays constant, and increasing battery demand contributes to growing graphite demand. Similar to lithium, the annual demand for graphite, which is only marginally impacted by the cathode material, does not differ much between the Baseline and High LFP Share scenario, with 2% more graphite in the latter than in the former in 2030 and 1% more in 2040. As sodium-ion batteries use hard carbon instead of graphite as the anode material, the High Sodium-Ion Battery Share scenario shows significantly lower annual demand for graphite than in the Baseline, recording levels 15% lower in 2030 and 16% lower in 2040.

Figure 13

Annual global raw material demand for lithium, nickel, cobalt, and graphite under the Baseline and alternative battery technology mix scenarios



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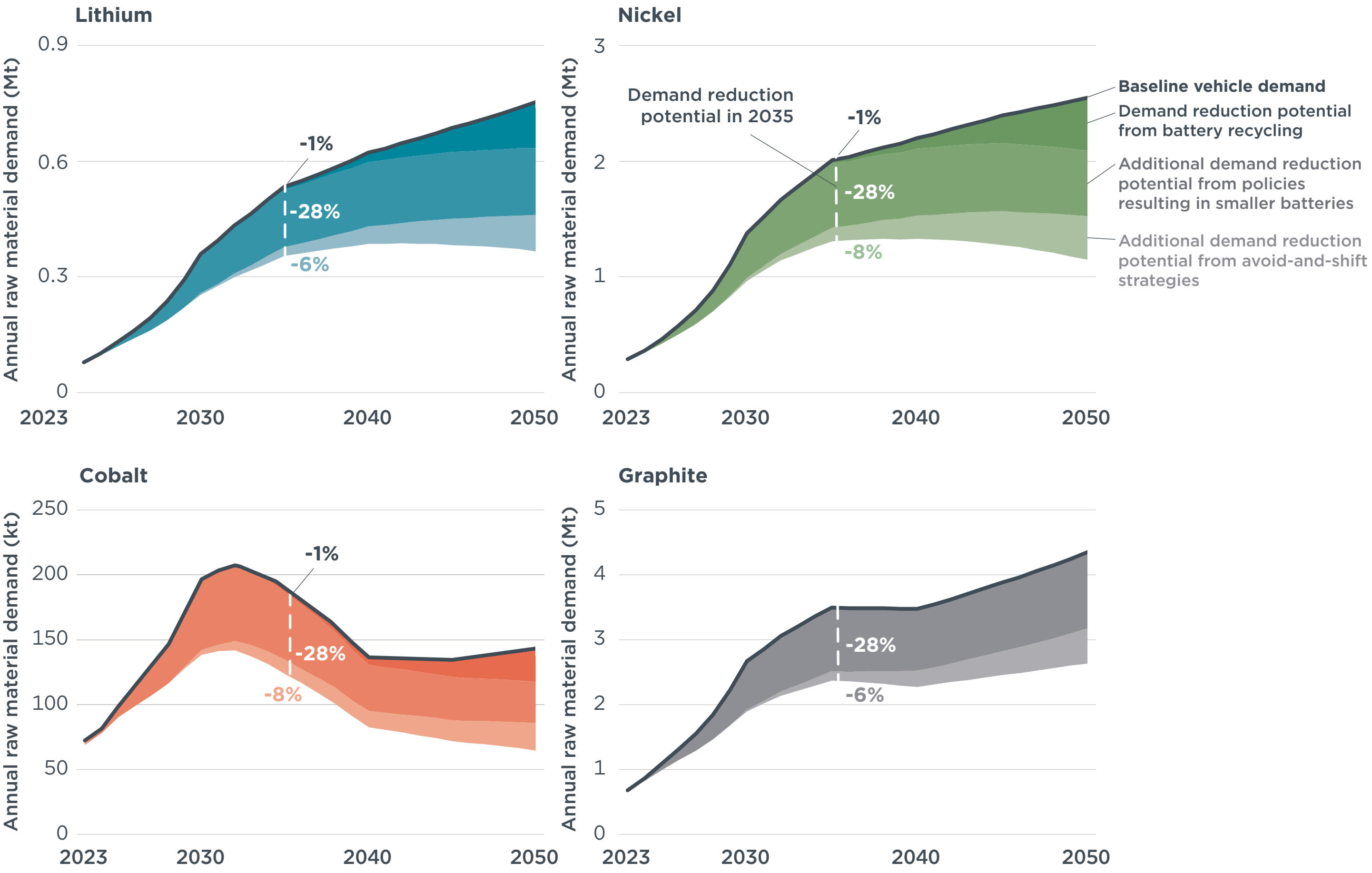
These raw material demand projections can be reduced by establishing an efficient battery recycling and mineral recovery environment, using smaller batteries, and reducing demand for private passenger car and on-road freight transport. Figure 14 shows how the demand for the selected materials changes in three alternate scenarios: the Global Recycling scenario, Smaller Batteries scenario, and Avoid-and-Shift scenario.

In the Global Recycling scenario, lithium, nickel, and cobalt demand all grow at a slower rate with the start of mandated material recovery in 2027. Notably, the impacts of battery recycling on raw material demand occur later than the impacts of the other demand-reduction approaches: With a delay between current uptake of BEVs and PHEVs and the time their batteries become available for recycling, higher volumes of avoided demand only begin to materialize in the late 2030s (Tankou et al., 2023a). The recovery of graphite is difficult with current recycling technologies and not covered under the EU regulation, so the figure for graphite shows the same level of demand for the Baseline and Global Recycling scenarios. The Smaller Batteries and Avoid-and-Shift scenarios are depicted in the bottom two slices of each figure, respectively.

Figure 14

Annual global raw material demand for lithium, nickel, cobalt, and graphite under the Baseline and demand reduction scenarios



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To illustrate the relative impacts of recycling, smaller vehicle batteries, and lower demand for vehicles overall, the white dashed line in Figure 14 shows the influence of the three factors on the annual raw material demand in 2035. As noted above, recycling makes a relatively small contribution to the reductions in annual raw material demand in 2035 (of 1% for lithium, nickel, and cobalt). By contrast, a reduction in the average battery sizes of light-duty BEVs shows a faster and more direct impact on raw material demand, reducing it by 28% for all materials relative to the Baseline, the largest decrease of the three alternate scenarios. This suggests that regulatory interventions that achieve smaller fleetwide average battery sizes have the highest near-term potential out of the three policies evaluated in this analysis to reduce material demand.

Lastly, avoid-and-shift strategies reduce passenger vehicle and freight truck sales and thereby reduce battery demand, with declines in raw material demand of 6%–8% in 2035. The complex regulatory, economic, and infrastructure interventions that encourage individuals to shift from private cars to public or active modes of transport take years to implement and influence passenger behavior. Similarly, avoid-and-shift policies in freight transport require a balance of infrastructure and economic measures, the impacts of which develop over several years. Thus, shifts in both passenger and freight transport away from private cars and trucks are assumed to steadily gain momentum, with their largest reductions in material use occurring after 2035.

In 2050, between 16% and 18% of annual primary raw material demand for lithium, nickel, and cobalt can be met through recovered material from recycled batteries. In the same year, this analysis projects smaller batteries will reduce annual demand for the five minerals considered in this analysis by an additional 27% from the Baseline scenario. Likewise, transport demand reduction and mode shift strategies are projected to reduce 2050 mineral demand by between 17% and 25% from the Baseline scenario.

The impact of the demand reduction measures in the High LFP Share and High Sodium-Ion Battery Share scenarios are presented in Figure A4 and Figure A5.

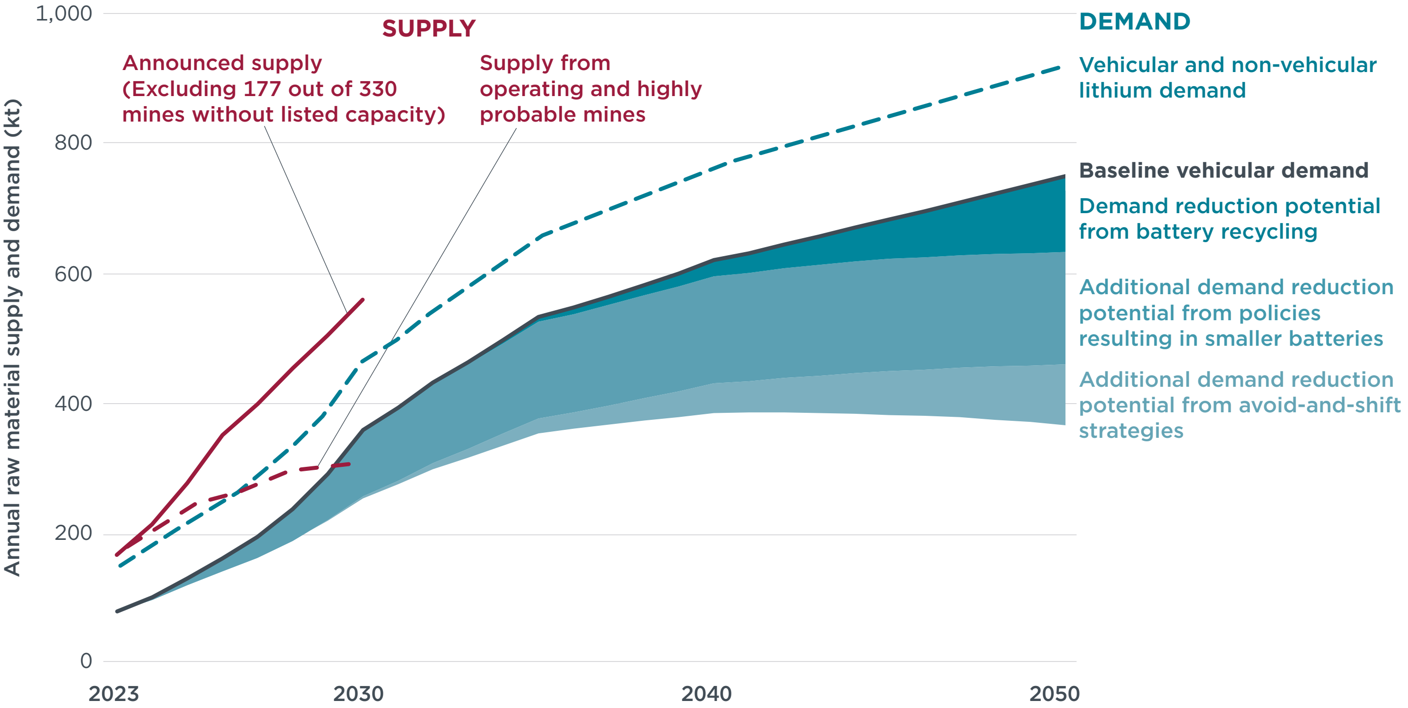
Comparison with announced mineral supply

Figure 15 compares the projected raw material demand for lithium with announced mining capacities. Indicated by the dashed blue line, this raw material demand accounts for vehicle demand as well as demand from non-vehicle lithium-ion batteries and from non-lithium-ion battery uses based on the IEA's critical mineral data explorer (IEA, 2024a). For mining capacities, the figure distinguishes between projects categorized by BMI (2022) as operational and highly probable (indicated by the dashed line) and total announced mining capacities, including projects BMI categorizes as probable or possible (solid line). Mining capacity values are reduced by a 5% yield loss rate and a 5% disruption factor. Notably, the total announced mining capacity does not include 177 of 330 mines in the BMI database for which no capacities were provided.

Comparing the lithium mining capacity data with projected vehicle and non-vehicular demand, the operational and highly probable mining capacities match 68% of the combined lithium demand in 2030. The total capacity of announced mining projects, even when excluding the 177 mines without capacity data, would correspond to 122% of the 2030 lithium demand from all sectors.

Figure 15

Annual global lithium raw material demand under the Baseline and demand reduction scenarios compared with announced mining capacity



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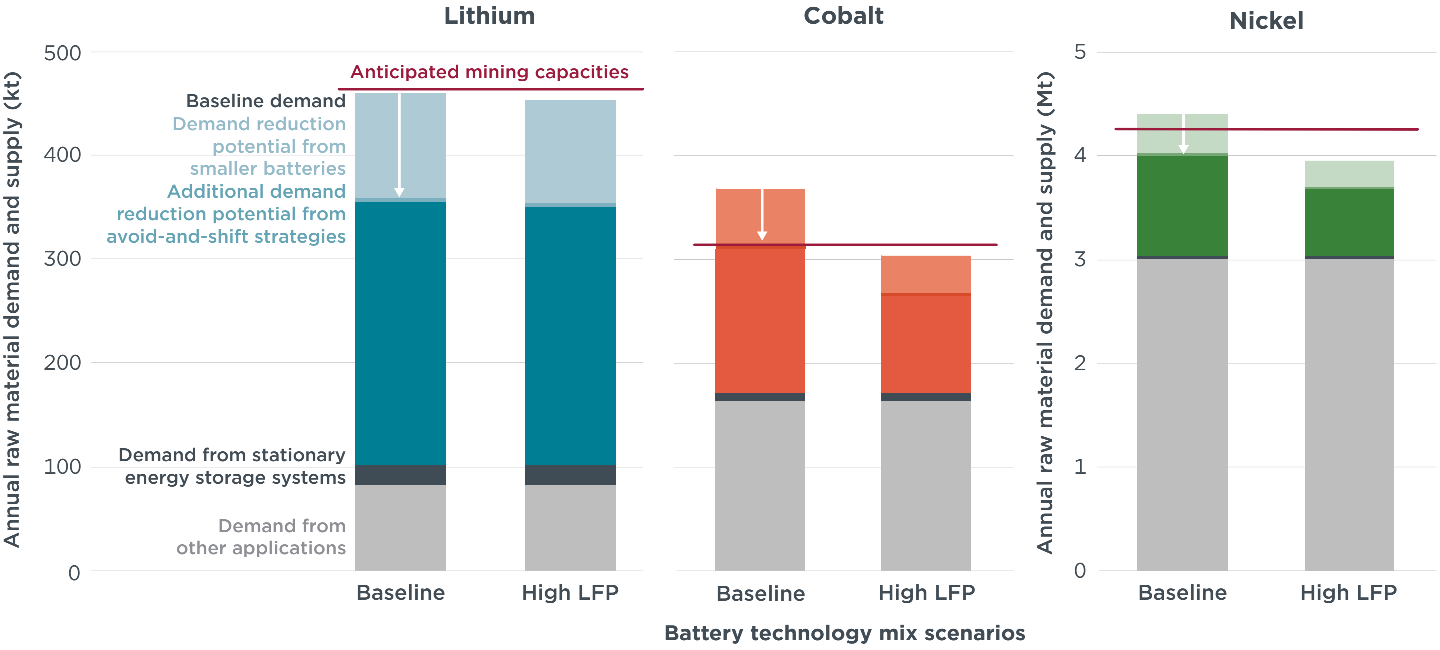
In between the supply outlook for all announced lithium mining capacities and only those that are operational or that have been announced and are considered highly probable, the IEA anticipates annual lithium mining capacities of 465 kt in 2030 (IEA, 2024b). This figure considers a partial realization of lithium mining capacities that are not operational or categorized as highly probable. The IEA's anticipated mining capacities of cobalt and nickel stand at 314 kt and 4.26 Mt, respectively. These supply figures are compared with the projected demand for each of these minerals from all sectors in 2030 under the different battery technology mix scenarios in Figure 16. The stacked columns indicate by how much the raw material demand could be reduced by recycling, reductions in the average battery capacity of light-duty BEVs, and reductions in passenger car sales and on-road freight transport activity. In addition to the estimated demand from road transport electrification, each column includes the mineral demand from batteries in stationary energy storage systems and portable electronics, as well as from non-battery applications, based on the IEA's Announced Policies Scenario (IEA, 2024a). A comparison of 2030 material demand and supply under the High Sodium-Ion Battery Share scenario is displayed in Figure A7.

Figure 16

Annual global raw material demand for lithium, cobalt, and nickel in 2030 by battery demand reduction scenario under the Baseline and High LFP Share battery technology mix scenarios compared with anticipated mining capacity



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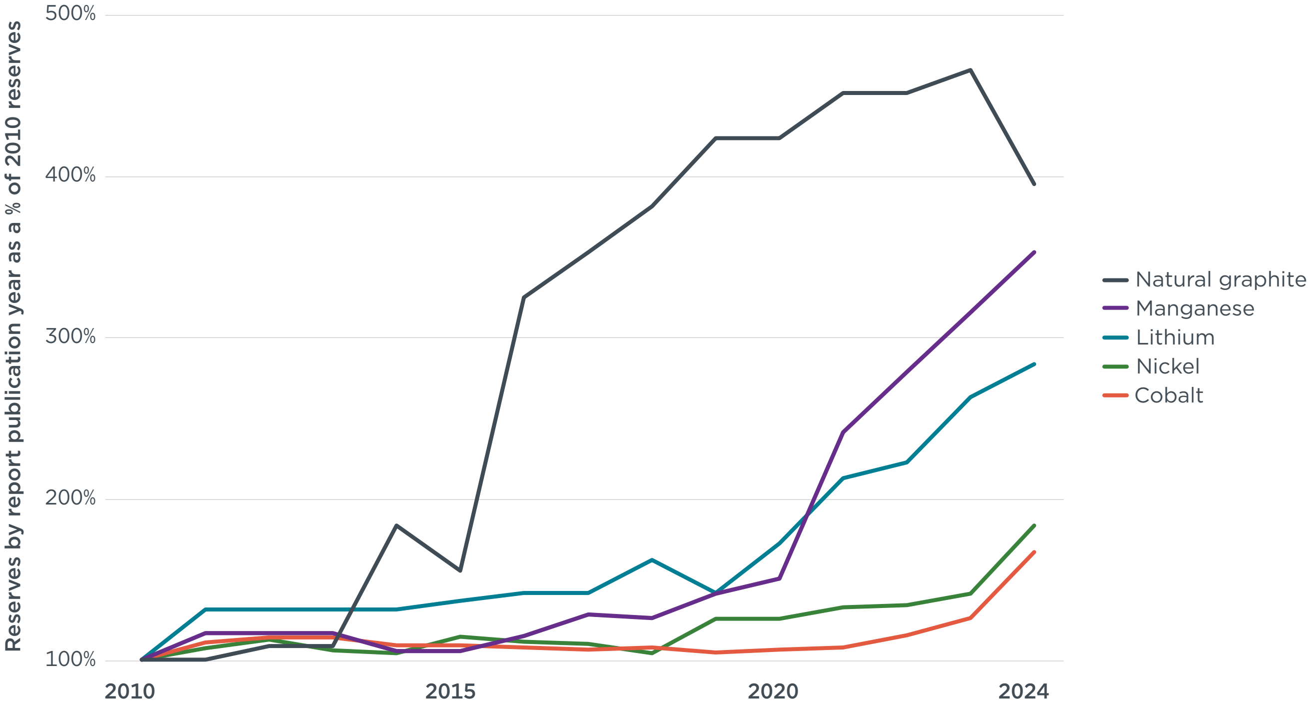
For the Baseline battery demand scenario, lithium demand stands at 461 kt in the Baseline technology mix scenario and 454 kt in the High LFP Share scenario. Anticipated lithium mining capacities meet 101% and 102%, respectively, of global demand in these scenarios. For the High Sodium-Ion Battery Share scenario, the 2030 demand in lithium is projected to be 400 kt, which is considerably less than the anticipated supply. Anticipated mining capacities for nickel meet 97% of the 4.4 Mt of projected demand in the Baseline scenario and 85% of the 369 kt of demand for cobalt. In the High LFP Share scenario, the demand for nickel and cobalt is estimated at 4.0 Mt and 304 kt, respectively, both below anticipated supply. In the High Sodium-Ion Battery Share scenario, nickel demand is similar to the Baseline (at 4.2 Mt) while cobalt demand is lower (at 304 kt). While this means that additional investments would be needed to ensure a sufficient supply in 2030, this also means that the upscaling of mining capacities is close to meeting the increase in demand.

When comparing the different demand scenarios, it can again be seen that recycling has a limited impact on the mineral demand in 2030, as few BEV and PHEV batteries become available for recycling in this timeframe. Reduced vehicle demand as a result of avoid-and-shift strategies also results in a small reduction in demand for the three materials in 2030. In contrast, across all three battery technology mix scenarios, a decrease in the average battery sizes of light-duty BEVs yields a large effect on the demand outlook in 2030.

Comparison with global reserves

Comparing projected mineral demand with global reserves can be useful for evaluating the long-term feasibility and sustainability of transport decarbonization pathways. Yet this metric can be misleading if taken out of context of historical trends in mineral exploration. The categorization of a demonstrated resource as a reserve reflects contemporary exploration, as well as technical and economic conditions. An increasing demand for specific minerals can lead to discoveries of new resources, the development of novel mining and processing techniques, and changes in the market economics. For these reasons, the global reserves of the key minerals considered in this study have grown continually over the last decade. Figure 17 presents the development of global land-based reserves relative to 2010 levels as reported in annual Mineral Commodity Summaries by the U.S. Geological Survey (2024). The sharp decrease in graphite reserves from 2023 to 2024 reflects a decrease in the reserves located in Türkiye in the 2024 U.S. Geological Survey data.

Figure 17
Global reserves by publication year of U.S. Geological Survey report as a percentage of 2010 reserves



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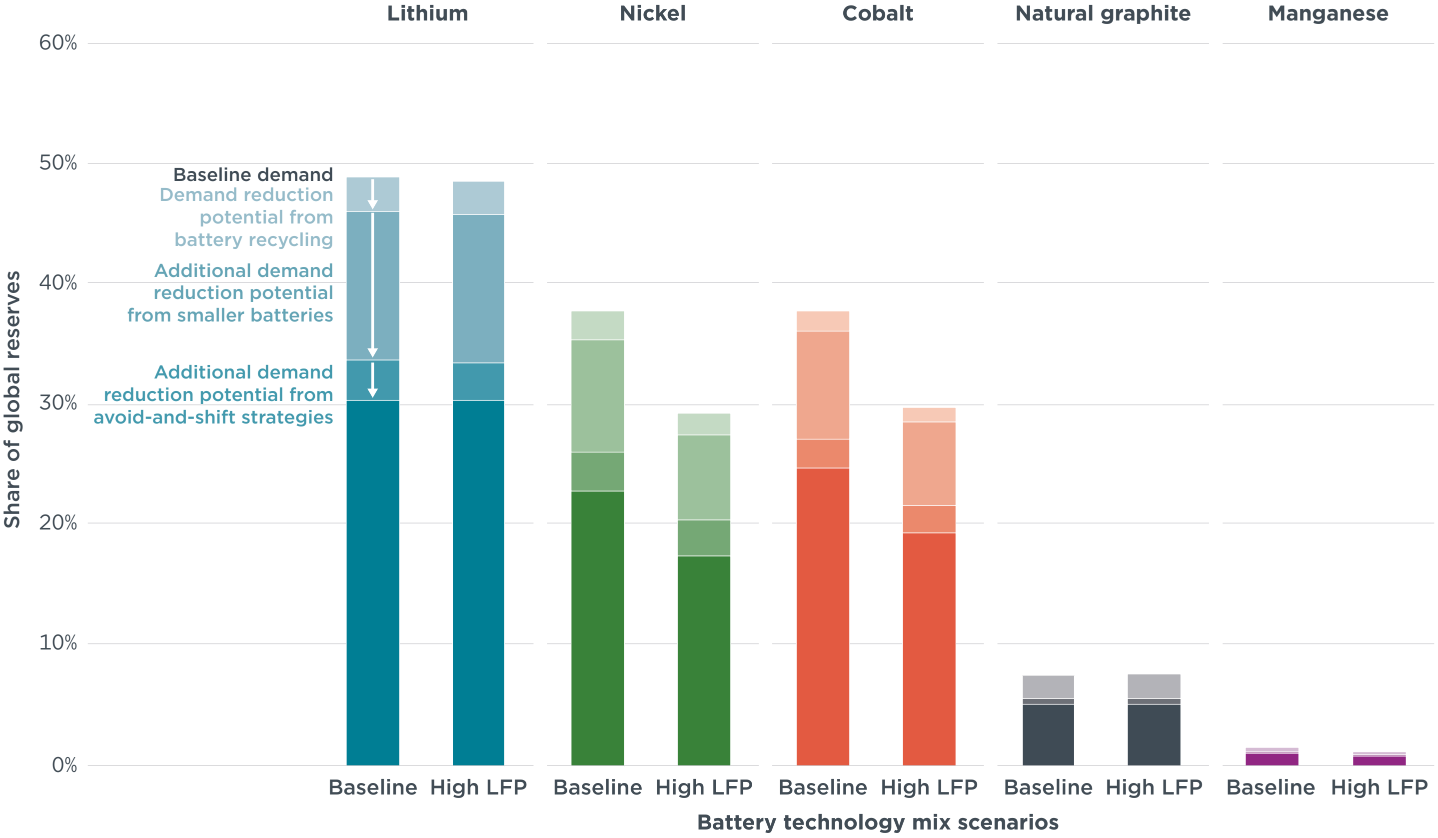
For lithium in particular, global reserves have increased by nearly a factor of three since 2010, and doubled since 2019 alone. This trend mirrors a growth in private investment in the exploration and development of new lithium resources over the last decade, with a spike in investment following record-high lithium carbonate prices in 2022 (S&P Global, 2023). On the one hand, increased lithium exploration has led to the discovery of new resources, which have increased by more than four times since 2010 (U.S.

Geological Survey, 2024). The discovery of lithium resources in India's Jammu and Kashmir union territory in early 2023 is an example of these efforts (Hendrix, 2023). Moreover, increased lithium prices can lead certain resources to become economically viable. On the other hand, investment in research has led to novel techniques that enable lithium to be economically extracted from previously costly or inaccessible deposits. For example, when operational, the Thacker Pass mine in the U.S. state of Nevada will use a novel technique to extract lithium from clay deposits. This deposit, which is estimated to contain 13.7 million tonnes of lithium carbonate equivalent, has been explored for lithium since 2007, but was only considered economically mineable after lithium-clay extraction techniques were improved in recent years. Acknowledging similar trends for the other minerals, it is likely that the reserves of all of the selected minerals will keep growing alongside increasing demand.

Figure 18 shows the cumulative mineral demand for BEV and PHEV batteries across the two- and three-wheeler, LDV, and HDV segments between 2023 and 2050 as a share of global land-based reserves in 2024 (U.S. Geological Survey, 2024). In the Baseline scenario, the cumulative demand for lithium reaches 49% of identified global reserves in 2050, followed by cobalt at 38%, nickel at 38%, and manganese at 2% of reserves. The projected demand for natural graphite corresponds to about 8% of global natural graphite reserves. This number considers only a portion of the total graphite demand, as today only 25% of lithium-ion batteries are produced with natural graphite, with the majority using synthetic graphite (BMI, 2023b). Moreover, the natural graphite demand does not consider losses that occur during natural graphite refining. The bars within each column indicate how global recycling, smaller batteries, and avoid-and-shift strategies would reduce this demand.

Figure 18

Cumulative raw material demand between 2023 and 2050 as a share of global reserves identified as of 2024, in the Baseline and High LFP Share battery technology mix scenarios



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Overall, it is important to note that the underlying assumptions on the development of the market for battery technologies reflect a reasonable certainty in the short to medium term but are highly hypothetical in the longer term, especially when considering a time horizon until 2050. The projected material demand can thus be considered a conservative estimate that is likely to overestimate the actual mineral demand in the longer term. In the High LFP Share scenario, the share of global reserves needed to meet the cumulative demand for lithium and graphite is equivalent to that in the Baseline scenario. Shares of nickel and cobalt reserves required to meet cumulative demand for vehicle electrification under the High LFP Share scenario, in contrast, fall to 29% and 30%, respectively.

Figure A8 displays the cumulative material demand in the alternative High Sodium-Ion Battery Share scenario, in which the demand for the selected raw materials is lower than in the Baseline except for nickel and manganese due to the use of these materials in layered oxide cathodes.

CHINA

VEHICLE SALES

This study estimates the battery material demand from BEV and PHEV sales needed to meet adopted and currently discussed policies and targets. The BEV and PHEV sales are generally based on the Political Momentum scenario by Sen and Miller (2023), updated with 2023 LDV sales shares from Fadhil and Shen (2024) and more recent policy targets. For China, this study accounts for the unofficial target, proposed in the China Society of Automotive Engineers and China Automotive Research Center (CATARC)'s *Automotive Industry Green and Low-Carbon Development Roadmap 1.0*, that 60% of new sales of cars, buses, and trucks be NEVs by 2030 (CATARC, 2023).[7] This study further adopts provincial-level policies considered in Sen and Miller (2023)—including those in Beijing, Guangdong, Hainan, and Shanghai—which mainly consist of NEV sales targets for passenger vehicles and public fleets in the 2025–2030 time frame. BEV and PHEV sales that exceed these policies and targets, such as those of potential future policies and market developments resulting from the ongoing decline of BEV costs, are not covered. As there are currently no vehicle electrification targets beyond 2030, projected BEV and PHEV sales shares after 2030 likely underestimate the actual market development, especially in the LDV and HDV segments. For two- and three-wheelers, however, the estimated sales do account for such market development to some extent, as the IEA scenario on which they are based was designed to cover economic dynamics beyond the impact of the considered electrification policies and targets.

As displayed in Table 3, considering current policies and targets, BEV and PHEV sales shares reach 60% for new light-duty vehicle sales nationwide in 2030 and remain constant thereafter. The assessment assumes that most of these combined BEV and PHEV sales will be BEVs, with PHEV sales shares decreasing from 10% in 2023 to 4% in 2030 and 3% thereafter. This split of BEV and PHEV sales is considered a conservative estimate for the battery material demand. In fact, given the doubling of the PHEV sales share from 5% in 2022 to 10% in 2023 (Fadhil & Shen, 2024), some analysts expect that the PHEV and BEV sales share could reach a 1:1 ratio by 2025 (China EV100, 2024). For two- and three-wheelers, which already have a higher BEV share in 2023 than other vehicle segments, this study projects 86% of sales in 2050 to be BEVs.

Table 3
Projected BEV and PHEV sales shares for new vehicle sales in China

	2023	2030	2040	2050
Two- and three-wheeler BEV	35%	58%	71%	86%
Light-duty BEV	22%	56%	57%	57%
Light-duty PHEV	10%	4%	3%	3%
Medium-duty BEV	16%	26%	26%	26%
Heavy-duty BEV	2%	7%	10%	14%
Bus BEV	37%	50%	55%	56%

The Baseline scenario projects that combined vehicles sales of all powertrain types will increase markedly between 2023 and 2050. As detailed in Table A2, sales of two- and three-wheelers are expected to increase from 43 million to 61 million, sales of LDVs

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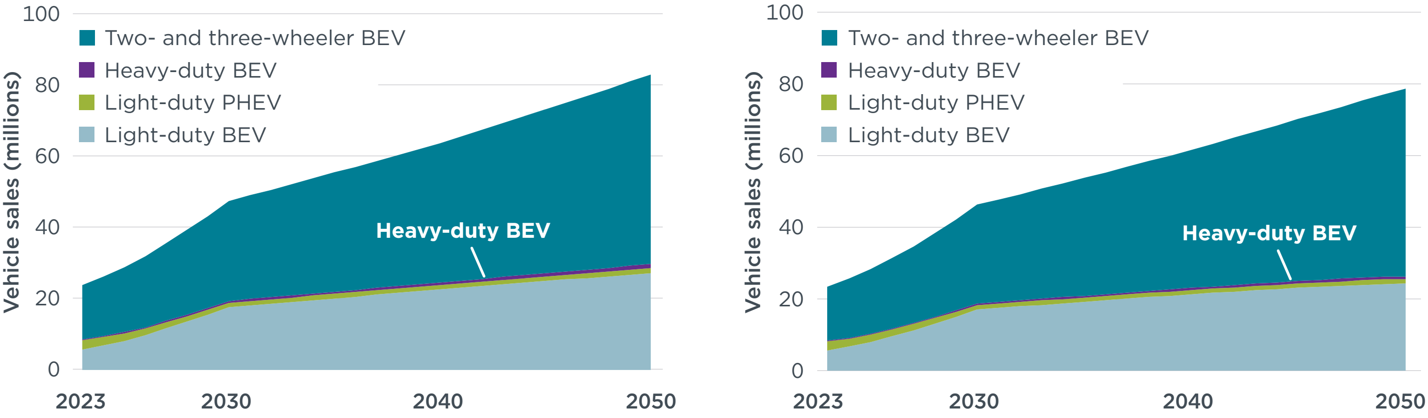
[7] New energy vehicles include BEVs, PHEVs, and FCEVs.

almost double from 25 million to 47 million, sales of buses nearly quadruple from 171,000 to 700,000, and MDT and HDT sales combined increase from 1.1 million to 3.1 million. Together with the assumed BEV and PHEV sales shares, these projections translate into combined BEV and PHEV sales across all segments of 23 million in 2023 and 81 million in 2050, as pictured in Figure 19 (left).

Figure 19

Projected annual BEV and PHEV sales in China in the Baseline (left) and Avoid-and-Shift (right) scenarios, by segment



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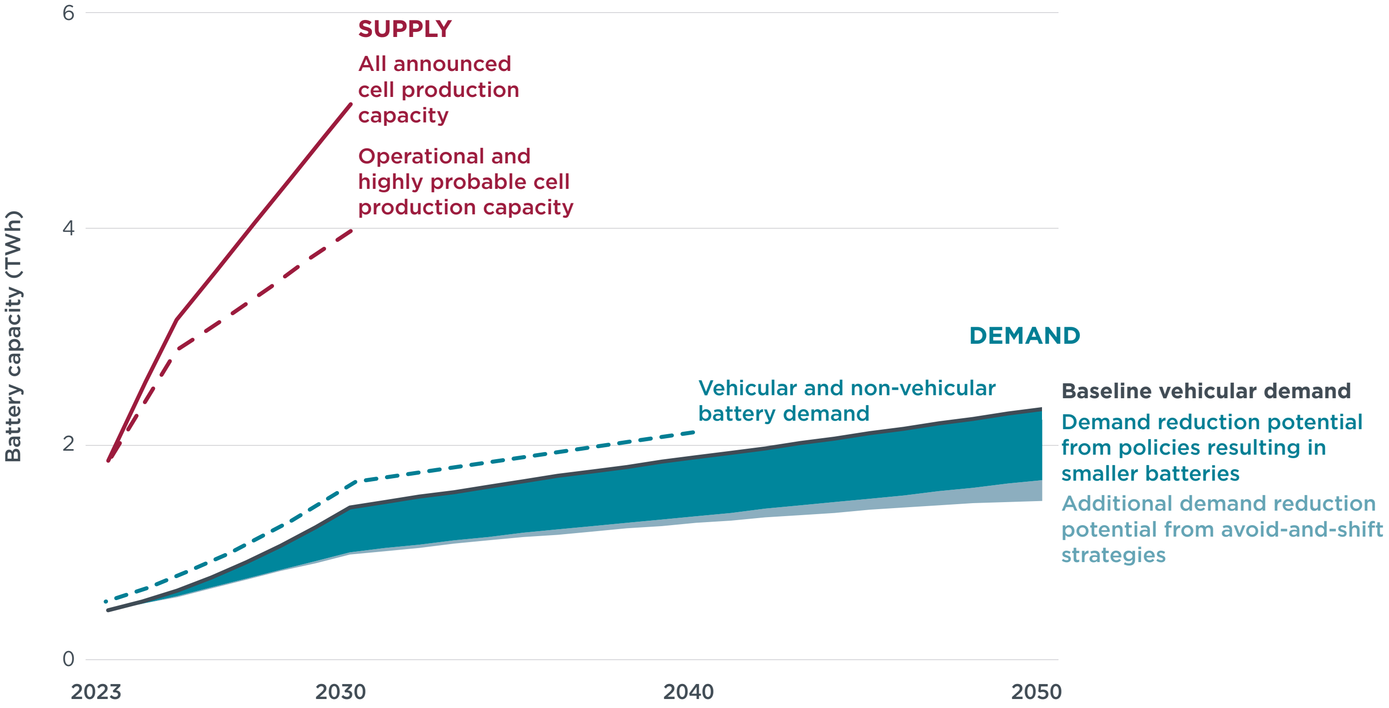
In the Avoid-and-Shift scenario, BEV and PHEV sales shares are the same as in the Baseline, but the total number of sales changes. As illustrated in the graph on the right of Figure *19* and detailed in Table A2, as of 2050, BEV and PHEV sales across all segments in this scenario (78 million) are 4% lower than in the Baseline (81 million). This is mainly due to a 75% reduction in sales of light commercial vehicles and a 48% reduction in sales of MDTs and HDTs. Light-duty passenger vehicle sales, however, are projected to decrease by only 3%, as the scenario considers that in China, a reduction in private passenger car travel activity would largely be offset by increased ride- and carsharing (see Table A1).

BATTERY DEMAND AND CELL PRODUCTION

This analysis projects that meeting the policies and targets considered for the Chinese road transport sector would result in an increase in battery capacity demand for BEVs and PHEVs from 0.4 TWh in 2023 to 1.4 TWh in 2030 and 1.8 TWh in 2040, as displayed in Figure 20. Adding BMI (2024b) estimates on non-vehicular battery capacity demand, which is mainly made up of demand for stationary energy storage systems, the total battery capacity demand increases from 0.5 TWh in 2023 to 1.6 TWh in 2030 and 2.1 TWh in 2040. This means that current demand would more than triple by 2030 and increase by a factor of four by 2040. In the Smaller Batteries scenario, the annual battery capacity demand for meeting the transport electrification targets is 30% lower in both 2030 and 2040. The Avoid-and-Shift scenario shows an additional reduction of 2% in 2030 and 5% in 2040.

Figure 20

Annual battery demand in China by demand reduction scenario compared with announced cell production capacity



Note: This demand projection excludes lead-acid batteries. Cell supply and non-vehicular demand data is sourced from BMI (2024a).

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Announced cell production capacities in China, as determined by BMI (2024a), substantially exceed the estimated domestic demand. Considering all cell production capacities that have already been announced, the 2030 supply exceeds domestic demand in the Baseline scenario by a factor of three. Even when only considering facilities that are already operational and those that are under construction and considered by BMI to be highly probable to reach announced capacities, the overall capacity is more than double domestic demand. This suggests that China could achieve more ambitious vehicle electrification targets with domestically produced batteries. Additionally, these capacities suggest a portion of Chinese battery production is likely to be exported to other markets.

MATERIAL DEMAND

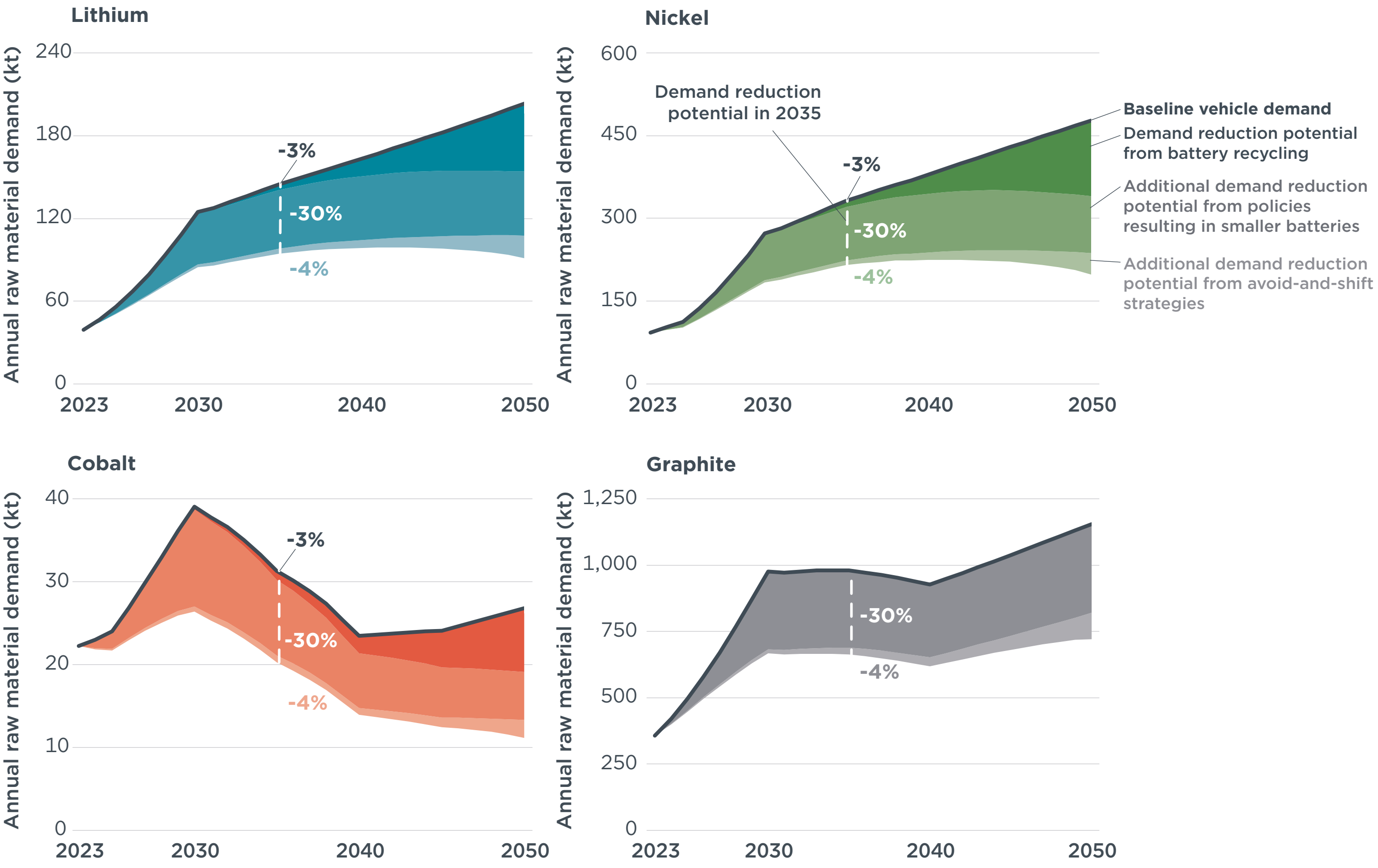
We translate projected battery demand into raw material demand for lithium, nickel, cobalt, graphite, and manganese based on scenarios concerning the future development of the battery technology mix. In the Baseline scenario, displayed in Figure 21, the demand for lithium continuously increases from 39 kt in 2023 to 125 kt in 2030 and 163 kt in 2040. Similarly, nickel demand increases from 93 kt in 2023 to 273 kt in 2030 and 379 kt in 2040, as the trend towards high-nickel NMC variants within the family of NMC cathodes more than compensates for the lower overall market shares of NMC batteries. The demand for cobalt, however, shows a slight increase from 23 kt in 2023 to 39 kt in 2030 but then falls back to 23 kt in 2040 due to an expected decrease in the overall market share of NMC batteries in China in combination with a shift to high-nickel, low-cobalt NMC variants within the family of NMC cathodes. The demand for graphite, meanwhile, increases steeply from 357 kt in 2023 to 976 kt in 2030, where it remains roughly constant until 2040. The consistent level of demand for graphite in the 2030s is due to the demand for graphite per kilowatt-hour of battery capacity decreasing with the increase in the considered share of silicon at the anode. This trend compensates for the increasing demand in battery capacity.

Figure A9 presents the projected material demand for the two alternative battery technology mix scenarios. In the High LFP Share scenario, with a higher share of LFP batteries, the relative share of NMC batteries decreases, which results in a lower demand for nickel and cobalt, while the demand for lithium and graphite is negligibly impacted by the share of LFP versus NMC batteries. If part of the market share of LFP batteries were replaced by sodium-ion batteries, as in the High Sodium-Ion Battery Share scenario, the demand for lithium, cobalt, and graphite would decrease substantially. In contrast, as the sodium-ion battery in this analysis contains nickel and manganese cathode material, the demand for these two minerals would increase.

Projected mineral demand in China could be reduced through policy interventions promoting an efficient battery recycling environment, smaller batteries, and transport demand avoidance and mode shift strategies. Figure 21 displays the impact of these strategies for the Baseline battery technology mix scenario. Recycling can reduce the annual demand for lithium, nickel, and cobalt by 3% in 2035 and by 24%–29% in 2050. As described above, large-scale demand avoidance in this scenario is subject to a delay of 15–25 years between the upscaling of BEV and PHEV production and the eventual recycling of these vehicles. With a reduction in battery sizes, the annual demand for assessed materials decreases by 30% in 2035 and by 29%–30% in 2050. Avoid-and-shift strategies reduce material demand by an additional 4% in 2035 and 12%–16% in 2050. Figure A10 shows the annual demand for manganese in China under the various demand reduction scenarios.

Figure 21

Annual raw material demand for lithium, nickel, cobalt, and graphite in China under the Baseline and demand reduction scenarios



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DOMESTIC MATERIAL RESERVES

Figure A*11* in the appendix compares the cumulative demand for lithium, nickel, cobalt, graphite, and manganese in China with domestic mineral reserves. China has ample reserves of manganese and natural graphite and considerable reserves of lithium and nickel, according to the U.S. Geological Survey (2024). Exploiting these reserves could meet some of the cumulative domestic demand of the Baseline scenario, with reserves of lithium sufficient to meet the demand from road transport electrification until between 2040 and 2050, and reserves of nickel sufficient until between 2030 and 2040. Domestic natural graphite and manganese reserves are sufficient to meet the demand from road transport electrification beyond 2050.

EUROPEAN UNION

VEHICLE SALES

BEV and PHEV sales shares in the European Union are based on the Political Momentum scenario in Sen and Miller (2023), which accounts for several EU-wide and Member State policies, along with updated 2023 LDV sales shares in Fadhil and Shen (2024). Key policies considered for the BEV and PHEV sales shares are the European Union's LDV CO_2 standards, mandating zero tailpipe CO_2 emission for all vehicles sold starting in 2035, and the HDV CO_2 standards recently agreed on by the European Council, the European Parliament, and the Council of the European Union, which mandate a 90% reduction in the CO_2 emissions of new MDTs, HDTs, coaches, and interurban buses sold from 2040 and a 100% reduction for city buses sold from 2035. BEV and PHEV sales that surpass these policies (e.g., due to market dynamics resulting from the ongoing decline in BEV costs) are not covered in this analysis.

Altogether, the policies correspond to a 100% BEV sales share for new LDVs in the European Union starting in 2035, with the sales share of light-duty PHEVs decreasing from 5% in 2030 to 0% in 2035. Buses, MDTs, and HDTs would approach an 88%–89% BEV sales share for new vehicles in 2040. The BEV and PHEV sales shares for new sales of all modeled on-road segments is displayed in Table 4.

Table 4

Projected BEV and PHEV sales shares for new vehicle sales in the European Union

	2023	2030	2040	2050
Two- and three-wheeler BEV	10%	16%	32%	64%
Light-duty BEV	14%	54%	100%	100%
Light-duty PHEV	7%	5%	0%	0%
Medium-duty BEV	5%	42%	87%	88%
Heavy-duty BEV	2%	42%	88%	89%
Bus BEV	13%	67%	88%	89%

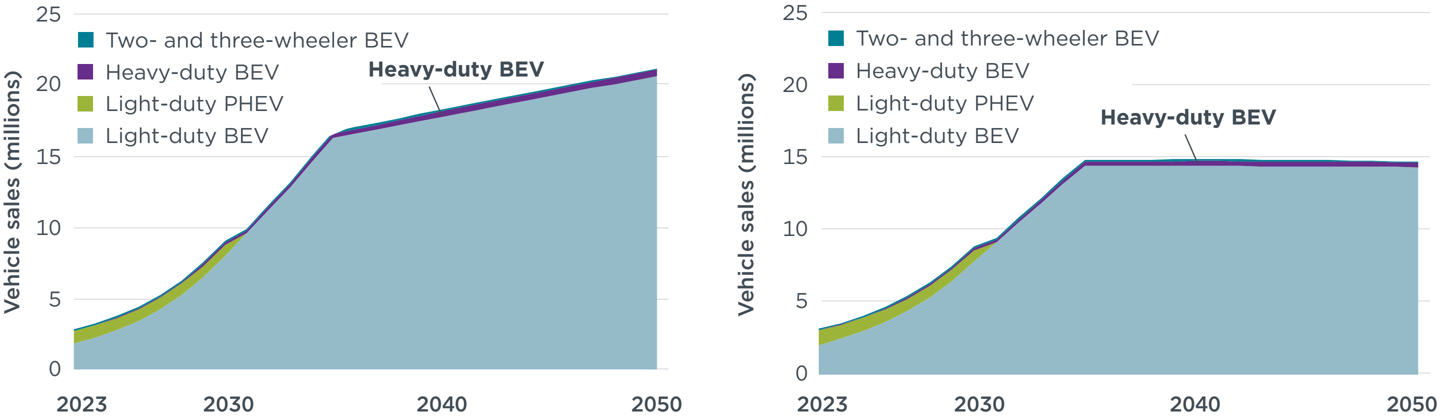
The Baseline scenario considers that sales of LDVs and HDVs of all powertrain types will increase between 2023 and 2050: As presented in Table A2, sales of LDVs increase from 13 million to 20 million, sales of buses double from 32,000 to 61,000, and MDT and HDT sales combined increase from 300,000 to 460,000. This large sales increase is based on the European Commission's EU Reference Scenario (ICCT, 2022). However, given the stagnation of EU LDV sales from 2001 to 2022 and economic downturns reducing LDV sales to below 10 million in 2013 and again in 2021–2022 from a high of 13 million in 2001 (Monteforte et al., 2024), the EU Reference Scenario is considered likely to overestimate future vehicle demand. In the Baseline scenario, this analysis projects annual BEV and PHEV sales in the European Union to grow by a factor of 7, from 3 million in 2023 to 21 million in 2050, as illustrated in Figure 22 (left).

In the Avoid-and-Shift scenario, displayed in Figure 22 (right), the BEV and PHEV sales shares for new vehicles are the same as in the Baseline scenario, but total vehicle sales change: In 2050, BEV and PHEV sales are a combined 15 million, 29% lower than in the Baseline. Sales of light-duty passenger cars decline by 29%, light commercial vehicles by 31%, HDTs by 27%, and MDTs by 34%. Sales of buses and two- and three-wheelers are assumed to remain the same as in the Baseline.

The large decrease in LDV sales in the Avoid-and-Shift scenario reflects the shift from private passenger car travel activity to public transit, walking and biking, carsharing, and two- and three-wheelers, as well as an overall reduction in passenger travel activity. The reduction in MDT and HDT sales is due to a combination of fewer freight vehicle kilometers traveled and an increase in the average fleetwide load factor. The assumed reduction in passenger car travel activity in the European Union is detailed in Table A1. The total vehicle sales in the Baseline and Avoid-and-Shift scenarios are listed in Table A2.

Figure 22

Projected annual BEV and PHEV sales in the European Union in the Baseline (left) and Avoid-and-Shift (right) scenarios, by segment



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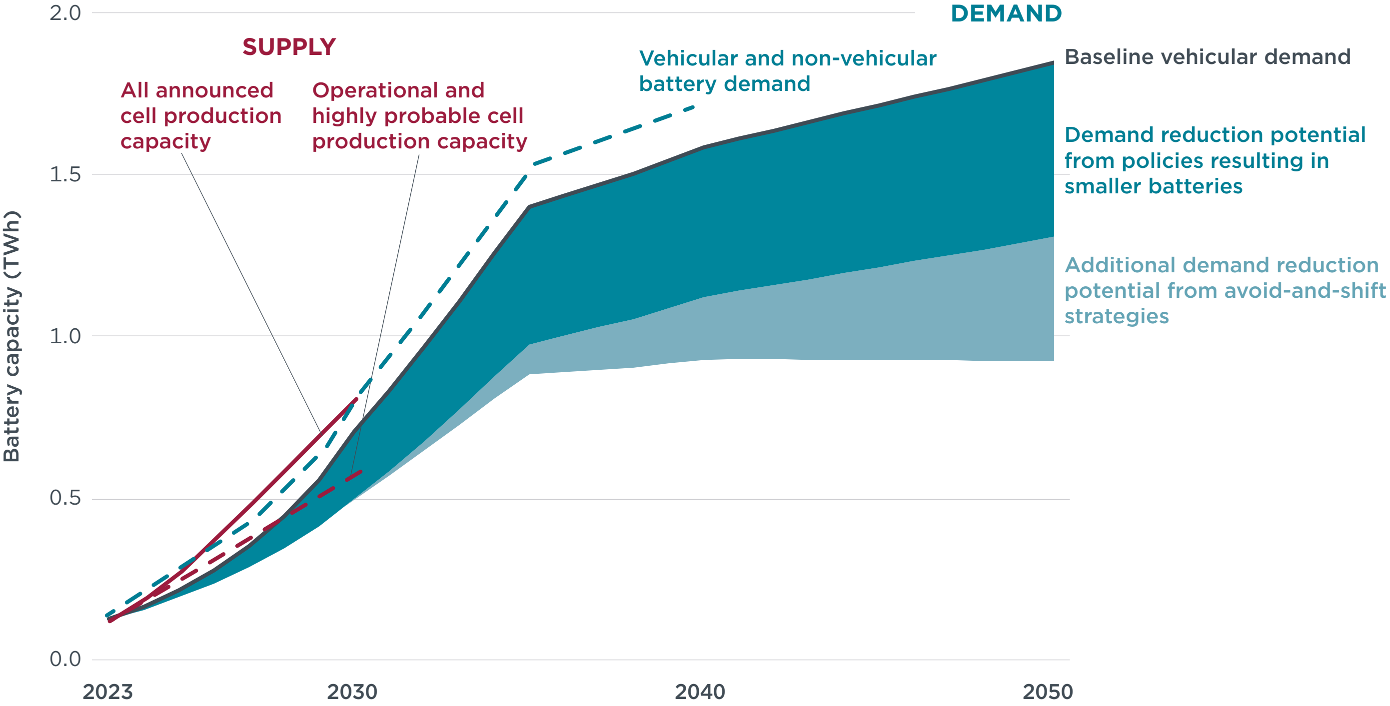
BATTERY DEMAND AND CELL PRODUCTION

This study projects that the considered policies, in combination with the Baseline scenario's assumed EU-wide growth in vehicle sales, would result in battery demand for BEVs and PHEVs increasing from 136 GWh in 2023 to 712 GWh in 2030 and 1.6 TWh in 2040, as displayed in Figure 23. Adding BMI (2024b) estimates on non-vehicular battery capacity demand, including for portable electronics and stationary energy storage systems, the total battery capacity demand increases from 164 GWh in 2023 to 807 GWh in 2030 and 1.7 TWh in 2040. In the Smaller Batteries scenario, the annual battery capacity demand for transport electrification is 29% lower in both 2030 and 2040. The Avoid-and-Shift scenario shows a negligible difference in 2030, but an additional reduction of 17% in 2040.

Total announced cell production capacities in the European Union, as reported by BMI (2024a), are projected to meet 99% of domestic demand from all sectors in 2030 if all projects are realized. The announced capacities generally reflect the status quo as of July 2024, but the capacity of Northvolt projects in Sweden were removed in reaction to the company filing bankruptcy in November 2024. Considering only the proportion of cell production facilities that are already operational and those that are currently under construction and considered by BMI to be highly probable to reach their announced capacity, the proportion of domestic battery demand met by domestic production capacity declines to 72% in 2030. This difference highlights the importance of ensuring that more of the announced investments will eventually be realized. In a scenario with smaller batteries for light-duty BEVs, 96% of the the 2030 demand would be covered by the plants already operational and those under construction that are considered highly probable to reach the announced capacities.

Figure 23

Annual battery demand in the European Union by demand reduction scenario compared with announced cell production capacity



Note: This demand projection excludes lead-acid batteries. Cell supply and non-vehicular demand data are sourced from BMI (2024a).

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MATERIAL DEMAND

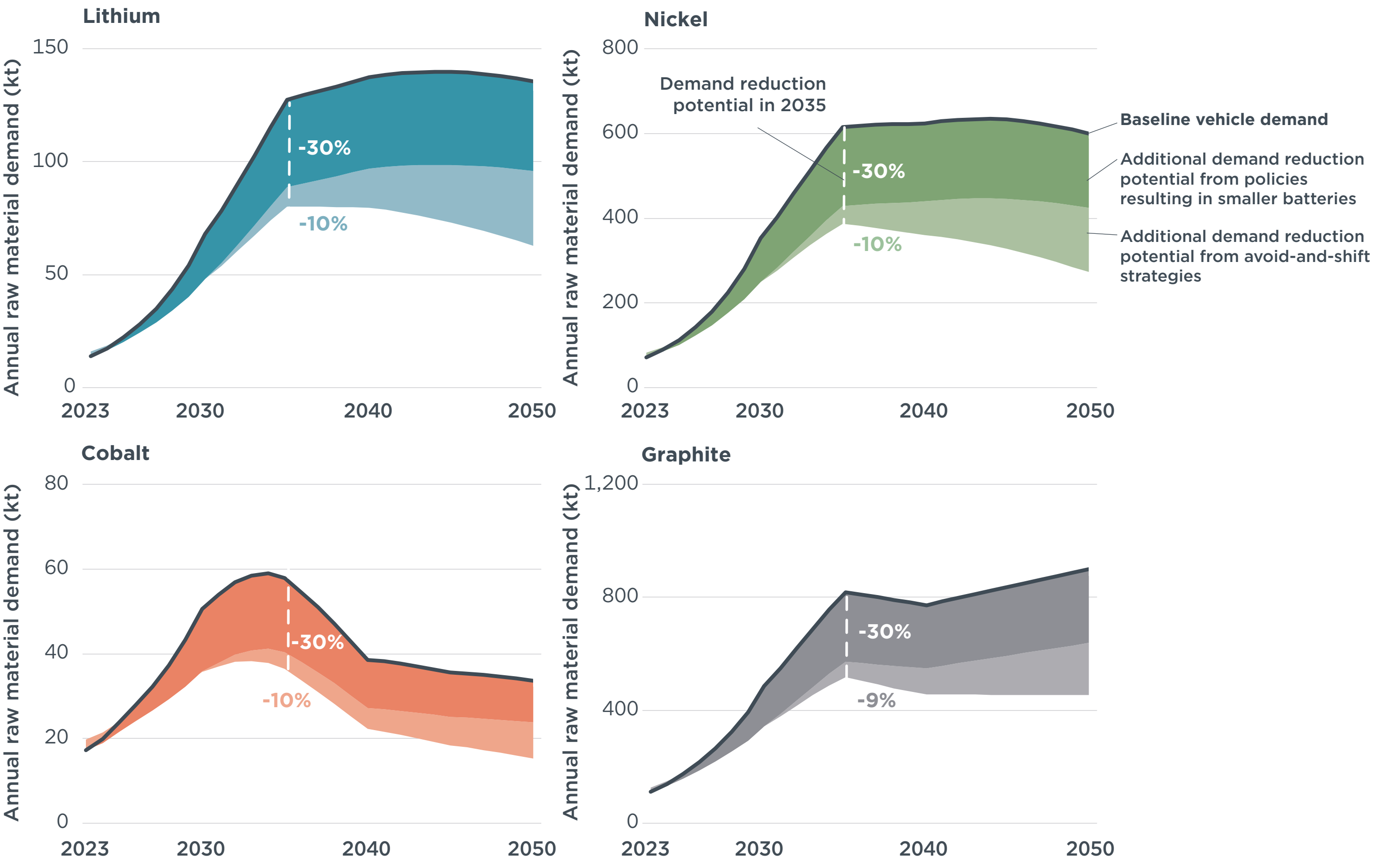
We convert the projected battery demand in the European Union into raw material demand for lithium, nickel, cobalt, graphite, and manganese based on scenarios for the future development of the battery technology mix. Figure 24 displays how projected battery demand in the Baseline scenario translates into raw material demand for lithium, nickel, cobalt, graphite, and manganese. In this scenario, the demand for lithium continuously increases from 14 kt in 2023 to 68 kt in 2030 and 137 kt in 2040. Similarly, nickel demand increases from 71 kt in 2023 to 353 kt in 2030 and 623 kt in 2040, reflecting the growing share of high-nickel, low-cobalt variants of NMC cathodes, such as NMC811 and NMC955, through 2040. The demand for cobalt, however, increases from 17 kt in 2023 to 51 kt in 2030 but then falls to 39 kt in 2040 due to the change in the variants of NMC cathodes and the overall decrease in the market share of NMC batteries. The demand for graphite increases rapidly from 110 kt in 2023 to 485 kt in 2030 and 773 kt in 2040. The lower growth rate of graphite demand in the 2040s is due to the decreasing demand for graphite per kilowatt-hour of battery capacity with the assumed increase in the share of silicon at the anode. This trend compensates for the increasing demand in battery capacity.

Figure A12 in the appendix highlights how projected demand varies with alternative battery technology market share scenarios. In the High LFP Share scenario, the relative share of NMC batteries decreases, which results in a lower demand for nickel and cobalt. The demand for lithium and graphite, in contrast, is negligibly impacted by the share of LFP versus NMC batteries. If part of the market share of LFP batteries were replaced by sodium-ion batteries, as highlighted in the High Sodium-Ion Battery Share scenario, the demand for lithium, cobalt, and graphite would decrease significantly. In contrast, the demand for manganese and nickel would increase in the long term, due to the assumption that most sodium-ion batteries would use a nickel- and manganese-containing layered oxide cathode.

Annual mineral demand in the European Union can be altered through policy interventions resulting in smaller batteries and transport demand avoidance and mode shift strategies. For the Baseline battery technology mix scenario, Figure 24 displays the impact of these strategies. With a reduction in battery sizes, the annual demand for the assessed materials decreases by 30% in 2035 and 29% in 2050. This illustrates the large potential of right-sizing batteries in passenger cars to reduce material demand. Avoid-and-shift strategies could reduce material demand by additional 9%–10% in 2035 and 29%–36% in 2050. The larger reduction from avoid-and-shift strategies in 2050 reflects the time necessary for economic incentives and changes in infrastructure to reduce private passenger car and freight transport.

Figure 24

Annual raw material demand for lithium, nickel, cobalt, and graphite in the European Union under the Baseline and demand reduction scenarios



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DOMESTIC RESERVES

Figure A14 in the appendix compares the cumulative demand for lithium, nickel, cobalt, graphite, and manganese with mineral reserves in the European Union. Aside from substantial nickel reserves in the French overseas territory of New Caledonia and small lithium reserves in Portugal, the European Union has few domestic resources of battery minerals that are listed as reserves by the U.S. Geological Survey (2024). New Caledonian nickel reserves would be sufficient to meet the cumulative demand for nickel from road transport electrification through between 2040 and 2050. In addition to those deposits listed as reserves, Germany, Czech Republic, Spain, Finland, and Austria have significant lithium resources (U.S. Geolgical Survey, 2024). In close proximity to the European Union, Norway has sizable natural graphite reserves and Serbia has further lithium resources. This highlights the importance of prioritizing strategic trade partnerships with mineral producing countries and increasing domestic battery recycling capacity to secure and retain adequate resources to power the transition to BEVs and PHEVs in the European Union.

INDIA

VEHICLE SALES

BEV and PHEV sales shares in India are based on the Political Momentum scenario from Sen and Miller (2023) with updated 2023 LDV sales shares from Fadhil and Shen (2024). The scenario considers India's signing of the Glasgow Zero Emission Vehicles (ZEV) Declaration, committing it to achieve a 100% share of BEV and fuel-cell electric vehicle sales for LDVs by 2040, with an intermediate target of 30% BEV sales for light-duty passenger cars by 2030 (Accelerating to Zero Coalition, 2021). It also considers subnational-level policies in Assam, Chandigarh, Delhi, Goa, Haryana, and Maharashtra, which aim to increase the BEV share of new LDV sales to between 10% and 50% and of new HDV sales to between 25% and 100% by 2030 (Sen & Miller, 2023). On top of the policies and targets considered in Sen and Miller (2023), this study also considers a governmental target of 80% BEV sales for two- and three-wheelers by 2030 (The Economic Times, 2021). BEV and PHEV sales that go beyond meeting these policies and targets (i.e., due to market dynamics resulting from the ongoing decline of BEV costs) are not covered.

As displayed in Table 5, the cumulative impact of these policies corresponds to a 100% BEV sales share for new LDV sales from 2040, with two- and three-wheelers reaching that share in 2035. Buses are projected to reach a 50% BEV sales share by 2050.

Table 5
Projected BEV and PHEV sales shares for new vehicle sales in India

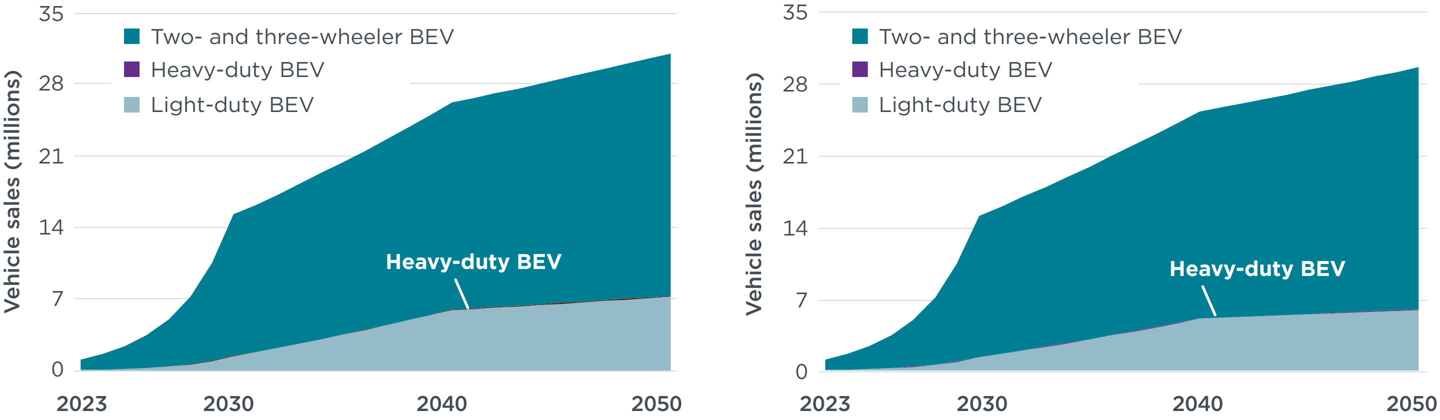
	2023	2030	2040	2050
Two- and three-wheeler BEV	7%	80%	100%	100%
Light-duty BEV	2%	31%	100%	100%
Light-duty PHEV	0%	0%	0%	0%
Medium-duty BEV	3%	10%	11%	20%
Heavy-duty BEV	2%	8%	9%	10%
Bus BEV	4%	12%	25%	50%

In the Baseline scenario, these BEV and PHEV sales shares are combined with total vehicle sales projections using the ICCT's India Emissions Model (ICCT, 2022). As presented in Table A2 in the appendix, this scenario projects that sales of two- and three-wheelers increase from 15 million to 24 million, sales of LDVs almost double from 3.7 million to 7.2 million, sales of buses increase by a factor of three from 41,000 to 133,000, and MDT and HDT sales collectively increase from 275,000 to 490,000. When combined with BEV and PHEV sales shares, the Baseline scenario projects annual BEV sales in India to increase exponentially between 2023 and 2050, arriving at about 31 million BEV sales across all segments in 2050, as illustrated in Figure 25 (left). PHEVs are expected to continue playing a negligible role in India. The majority of BEV sales are projected to come from the two- and three-wheeler segment, although LDV sales grow to make up 9% of total BEV and PHEV sales in 2030 and 23% in 2040.

In the Avoid-and-Shift scenario, BEV and PHEV sales shares are equivalent to those in the Baseline scenario but total sales of each segment change. Displayed in Figure 25 (right), total BEV sales in 2050 are 4% lower than in the Baseline scenario. This decrease is primarily due to reduced passenger car activity, which is 33% lower than in the Baseline scenario in 2050 (see Table A1) and translates to 21% lower LDV sales in 2050, as shown in Table A2. Sales of battery electric two- and three-wheelers and buses are assumed to stay the same in the Avoid-and-Shift scenario as in the Baseline. For freight transport, MDT and HDT sales in 2050 are 51% and 32% lower, respectively, than in the Baseline, due to a combination of fewer freight vehicle kilometers traveled and an increase in the average fleetwide load factor.

Figure 25

Projected annual BEV and PHEV sales in India in the Baseline (left) and Avoid-and-Shift (right) scenarios, by segment



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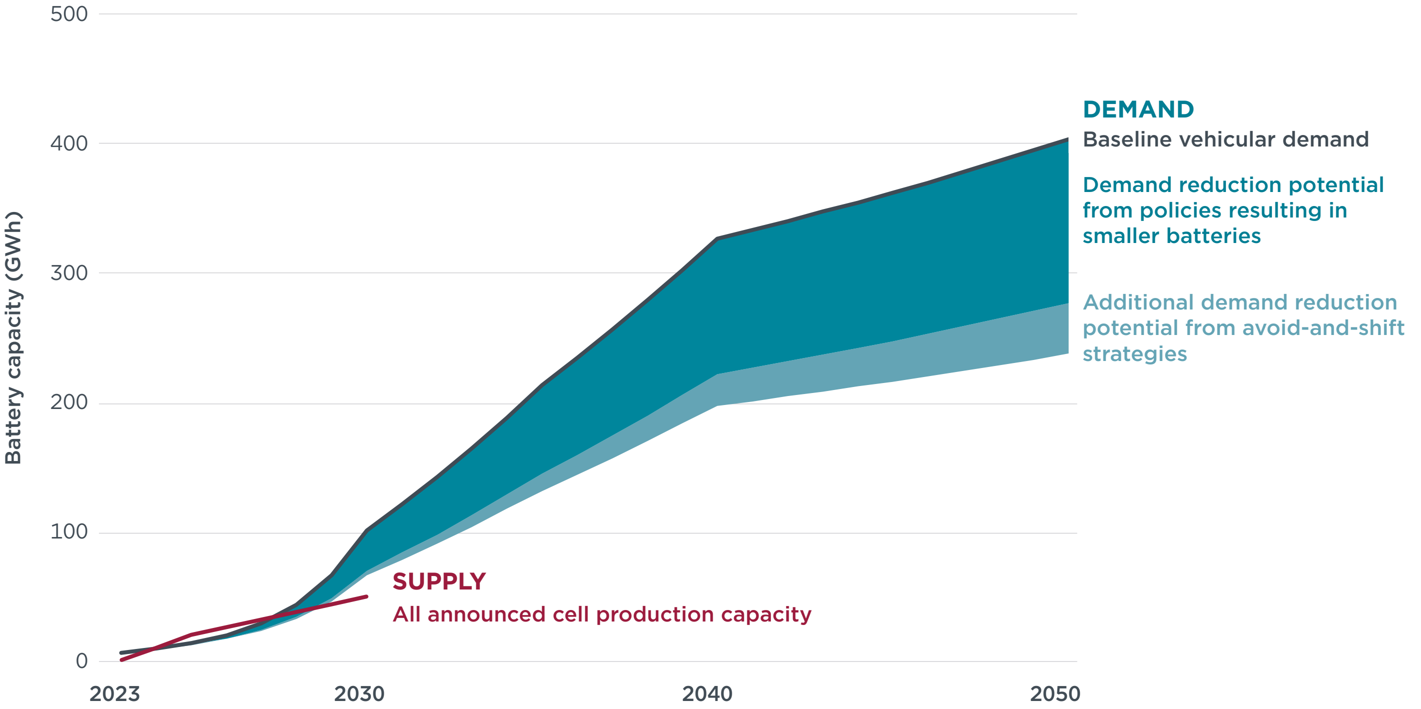
BATTERY DEMAND AND CELL PRODUCTION

This study estimates that meeting the vehicle electrification targets and policies considered for India would lead to an increase in battery capacity demand from 5 GWh in 2023 to 100 GWh in 2030 and 325 GWh in 2040, as displayed in Figure 26. In the Smaller Batteries scenario, the annual battery capacity demand is 31% lower in 2030 and 32% lower in 2040 than in the Baseline scenario. The Avoid-and-Shift scenario results in an additional reduction in battery demand of 6% in 2030 and 11% in 2040.

Although BMI (2024a) reports zero operational cell production capacity in India in 2023, several production facilities have been announced with plans to start operating in the mid-2020s. In 2030, the full realization of these capacities would meet 49% of the domestic battery demand from road transport in the Baseline scenario. In the Smaller Batteries scenario, announced cell production capacities in India would meet 71% of the domestic demand. The results of both scenarios indicate that additional investments would be needed to achieve self-sufficient domestic battery cell production in India. Leveraging India's existing auto manufacturing ecosystem to produce battery cells and electric vehicles could present an economic opportunity for this emerging BEV market.

Figure 26

Annual battery demand in India by demand reduction scenario compared with announced cell production capacity



Notes: This demand projection excludes lead acid batteries. Cell supply data are sourced from BMI (2024a).

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MATERIAL DEMAND

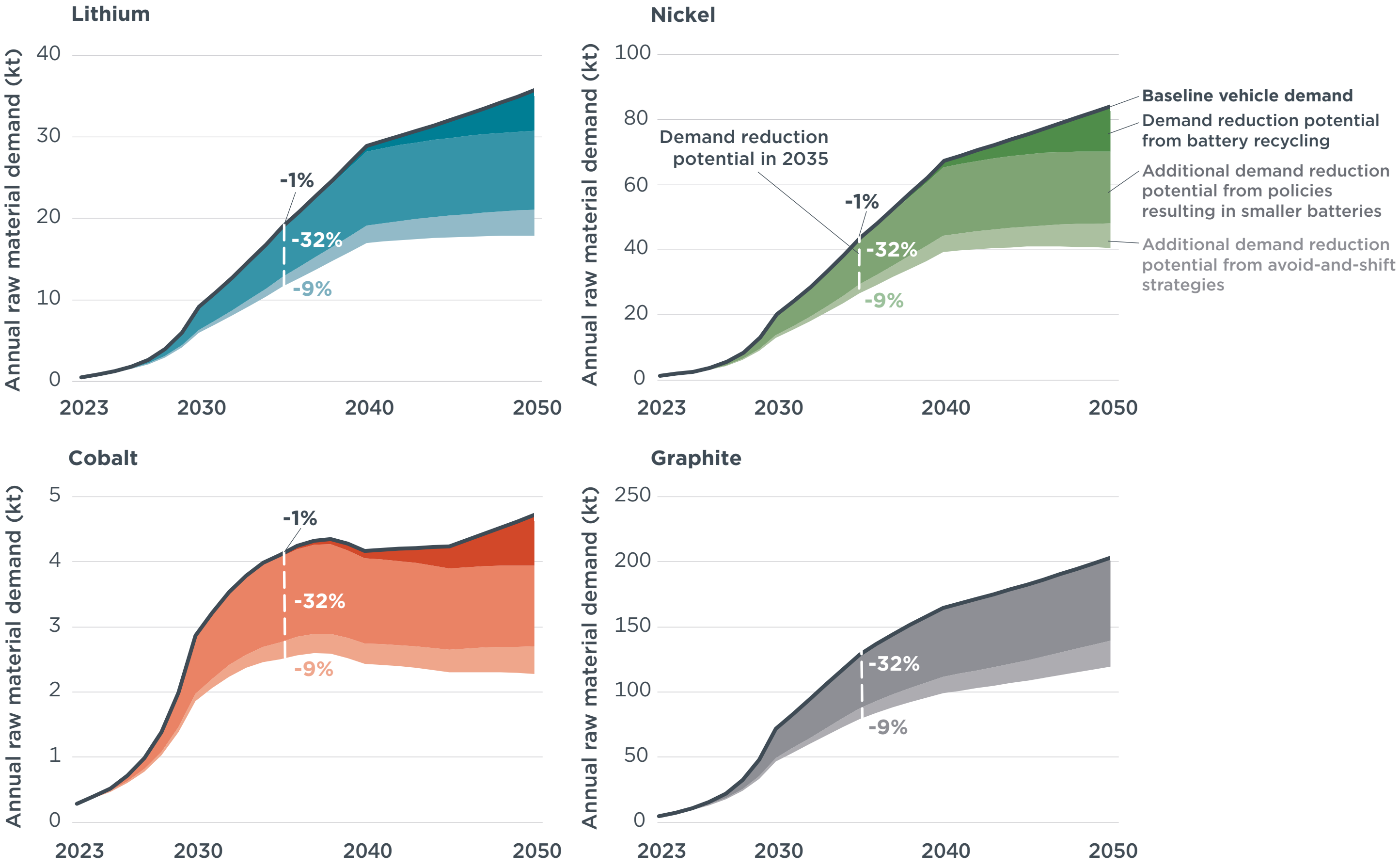
Translating the projected battery demand in India into raw material demand for lithium, nickel, cobalt, graphite, and manganese depends on scenarios for the future development of the mix of battery technologies. Figure 27 and Figure A16 in the appendix display how projected battery demand in the Baseline technology mix scenario translates into raw material demand for lithium, nickel, cobalt, graphite, and manganese. In this scenario, the demand for lithium increases from 0.5 kt in 2023 to 9 kt in 2030 and 29 kt in 2040. Similarly, nickel demand increases from 1 kt in 2023 to 20 kt in 2030 and 67 kt in 2040, as increasing BEV sales and the uptake of high-nickel, low-cobalt NMC variants such as NMC811 and NMC955 more than compensate for the declining overall market shares of NMC batteries. The demand for cobalt increases from 280 t in 2023 to 3 kt in 2030 and 4 kt in 2040. Despite the expected transition to low-cobalt NMC variants and more LFP batteries, the rapid increase in overall battery demand in India contributes to growing cobalt demand through 2050. The demand for graphite increases steeply from 4 kt in 2023 to 72 kt in 2030 and continues to grow to 164 kt in 2040. Like the increase in cobalt demand, growing demand for graphite is underpinned by the increase in overall battery demand, although the demand for graphite per kilowatt-hour of battery decreases with the assumed increase in the share of silicon in the anode.

In the High LFP Share scenario, as displayed in Figure A15 in the appendix, the growth in the LFP share contributes to proportional reductions in the market shares of NCA and NMC batteries, which result in a lower demand for nickel and cobalt. The demand for lithium and graphite, in contrast, is negligibly impacted by the share of LFP versus NMC batteries. In the High Sodium-Ion Battery Share scenario, which assumes a quarter of the market share of LFP batteries in the High LFP Share scenario are replaced by sodium-ion batteries in 2030, the demand for lithium, nickel, cobalt, and graphite decreases significantly. The demand for manganese, in contrast, increases, due to the assumption that most sodium-ion batteries would use a nickel- and manganese-containing layered oxide cathode.

Policies to encourage an efficient battery recycling environment, smaller batteries for passenger vehicles, and a reduction in passenger car and on-road freight transport demand can reduce the projected demand for raw materials in India. Figure 27 shows the impact of these strategies for the Baseline battery technology mix scenario. Recycling mandates of the same stringency as in the EU Battery Regulation reduce the annual demand for lithium, nickel, and cobalt by 1% in 2035 and 14%–17% in 2050. As in other markets, there is a delay in the demand reduction benefits of battery recycling, which is only expected to yield an increased volume of recovered material in India after 2040. With a reduction in average LDV battery sizes, annual demand for the selected materials decreases by 32% in 2035 and by 31% in 2050. Avoid-and-shift strategies reduce material demand by additional 9% in 2035 and 14%–16% in 2050.

Figure 27

Annual raw material demand for lithium, nickel, cobalt, and graphite in India under the Baseline and demand reduction scenarios



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DOMESTIC RESERVES

Figure A17 in the appendix compares the cumulative demand for lithium, nickel, cobalt, graphite, and manganese with mineral reserves in India. According to the U.S. Geological Survey (2024), India has ample reserves of manganese and natural graphite. Exploiting these reserves could meet some of the cumulative domestic demand of the Baseline scenario: Manganese and natural graphite reserves are sufficient to meet cumulative demand for vehicle electrification beyond 2050. Recently discovered lithium deposits in India's Jammu and Kashmir union territory are not considered here, as they have not yet been classified as reserves.

INDONESIA

VEHICLE SALES

BEV and PHEV sales shares in Indonesia are based on the Political Momentum scenario from Sen and Miller (2023), which includes targets of 2 million electric LDVs and 13 million electric motorcycles in the vehicle stock by 2030 (Ministry of Energy and Mineral Resources, 2021) and a 100% electric vehicle sales shares for two- and three-wheelers by 2040 and LDVs by 2050 (Reuters, 2021). In addition, this study considers production targets of 600,000 electric LDVs and HDVs annually by 2030 and 1 million electric LDVs and HDVs by 2035 (Indonesia Minister of Industry Regulation No. 6 of 2022, 2022). Finally, it assumes the electrification of all public transport by 2045 (Anam, 2024). BEV and PHEV sales that go beyond meeting these policies, such as those due to cost developments resulting in a faster and higher uptake than that set by the regulatory targets, are not covered.

These targets translate into 100% BEV sales shares for two- and three-wheelers and buses by 2040 and LDVs by 2050. BEV and PHEV sales shares for new sales of modeled segments are displayed in Table 6.

Table 6
Projected BEV and PHEV sales shares for new vehicle sales in Indonesia

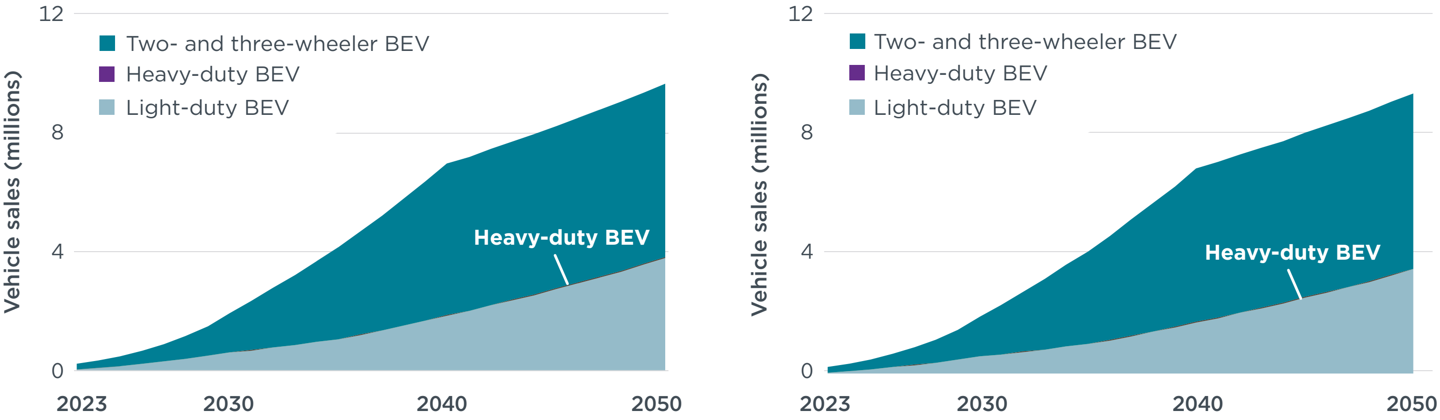
	2023	2030	2040	2050
Two- and three-wheeler BEV	5%	30%	100%	100%
Light-duty BEV	1%	35%	67%	100%
Light-duty PHEV	0%	0%	0%	0%
Medium-duty BEV	1%	2%	4%	10%
Heavy-duty BEV	1%	1%	3%	5%
Bus BEV	5%	30%	100%	100%

The Baseline scenario projects that in Indonesia, total vehicles sales increase markedly between 2023 and 2050: As presented in Table A2 in the appendix, sales of two- and three-wheelers increase from 4 million to 6 million, sales of LDVs increase from 750,000 to 3.7 million, sales of buses increase from 4,000 to 11,000, and combined sales of MDTs and HDTs increase from 100,000 to 305,000. Assuming the BEV sales shares above, this analysis projects annual BEV sales of 9.8 million in 2050, about 35 times the 2023 level, as illustrated in Figure 28 (left). Light-duty vehicles and two- and three-wheelers are projected make up 39% and 60% of BEV sales in 2050, respectively.

In the Avoid-and-Shift scenario, BEV sales shares are the same as in the Baseline scenario but the total sales volumes differ. As depicted in Figure 28 (right), 2050 sales of BEVs of all vehicle types decrease by 3%, from 9.8 million in the Baseline scenario to 9.5 million in the Avoid-and-Shift scenario. This is due to a reduction in 2050 passenger car activity by 16%, as displayed in Table A1, translating into a 7% reduction in 2050 passenger car sales. Battery electric two- and three-wheeler sales and bus sales are assumed to stay the same in the Avoid-and-Shift scenario as in the Baseline. In the Avoid-and-Shift scenario, sales of MDTs and HDTs in 2050 are 46%, and 31% lower, respectively, than in the Baseline in 2050 due to an assumed combination of fewer on-road freight vehicle kilometers traveled and an increase in the average fleetwide load factor. Vehicle sales data in the Baseline and Avoid-and-Shift scenarios are listed in Table A2.

Figure 28

Projected annual BEV and PHEV sales in Indonesia in Baseline (left) and Avoid-and-Shift (right) scenarios, by segment



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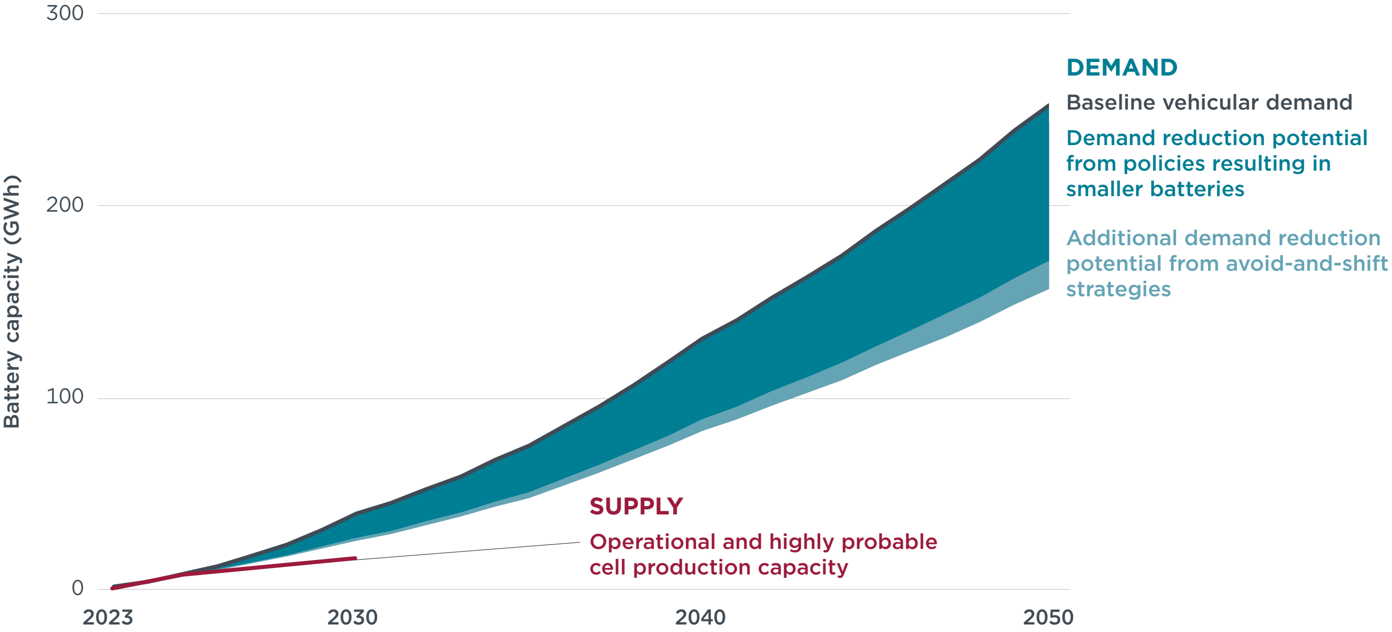
BATTERY DEMAND AND CELL PRODUCTION

Our analysis projects that a rapid scale-up of BEV sales in line with the targets considered for Indonesia would result in an increase in vehicle battery capacity demand from 0.8 GWh in 2023 to 39 GWh in 2030 and 130 GWh in 2040, as displayed in Figure 29. If the average battery size of passenger vehicles were to decrease by 20% instead of growing as expected, the total annual battery capacity demand for meeting the transport electrification targets would be 32% lower in both 2030 and 2040. The Avoid-and-Shift scenario shows an additional reduction in battery demand of 5% in 2030 and 7% in 2040.

In 2023, battery production facility data reported by BMI indicate zero operational capacity in Indonesia. However, there is a growing amount of cell production capacity planned or in development. Announced cell production capacities are projected to grow to 17 GWh in 2030. Realizing this capacity would allow Indonesia to meet 44% of domestic vehicular battery demand in 2030 in a Baseline scenario in which the average battery capacity of light-duty BEVs is assumed to increase by 20% by 2030. If it were instead to decrease by 20%, as presented in the Smaller Batteries scenario, the announced cell production capacities in India would meet 65% of domestic demand. In both scenarios, these results suggest that additional investments would be needed to promote self-sufficient domestic battery cell production in Indonesia.

Figure 29

Annual battery demand in Indonesia by demand reduction scenario compared with announced cell production capacity



Notes: This demand projection excludes lead acid batteries. Cell supply data are sourced from BMI (2024a).

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MATERIAL DEMAND

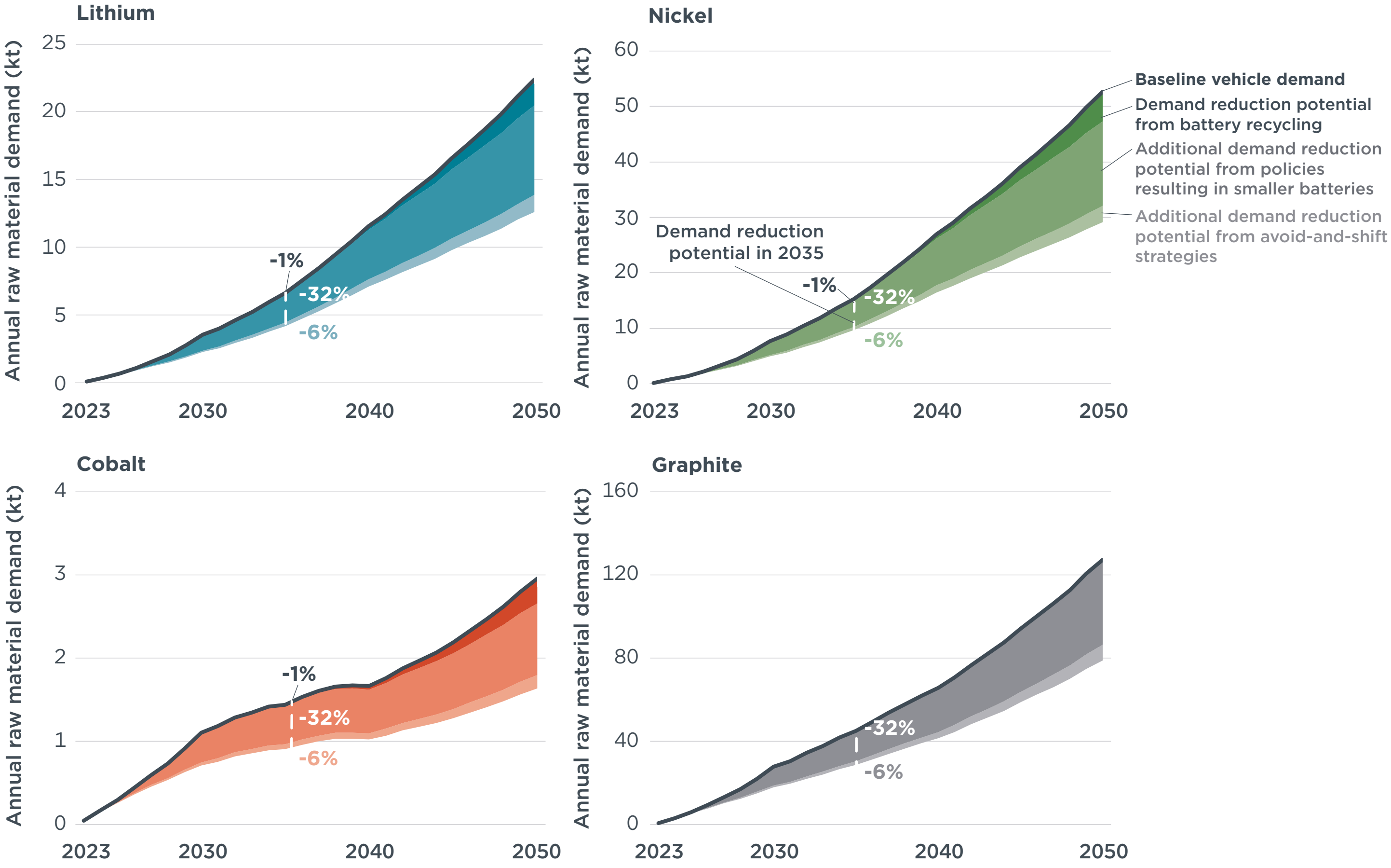
Translating the projected battery demand in Indonesia into raw material demand for lithium, nickel, cobalt, graphite, and manganese depends on scenarios for the future development of the battery technology mix. In the Baseline technology mix scenario, illustrated in Figure 30 and Figure A19 in the appendix, the demand for lithium continuously increases from 0.08 kt in 2023 to 4 kt in 2030 and 12 kt in 2040. Similarly, nickel demand increases from 0.18 kt in 2023 to 8 kt in 2030 and 27 kt in 2040. The demand for cobalt increases from 0.04 kt in 2023 to 1 kt in 2030 and 2 kt in 2040. Despite the expected transition to lower cobalt NMC variants, such as NMC811 and NMC955, the rapid increase in overall battery demand in Indonesia contributes to growing cobalt demand through 2050. The demand for graphite increases steeply from 0.68 kt in 2023 to 28 kt in 2030 and continues to grow to 66 kt in 2040. Similar to the increase in cobalt demand, the rapid increase in overall battery demand contributes to a continued growth in annual graphite demand, although the demand for graphite per kWh of battery decreases with the increase in the assumed share of silicon used at the anode.

Figure A18 in the appendix presents how this material demand outlook varies with alternative scenarios for the future development of battery technology market shares in Indonesia. Due to the availability of nickel and cobalt in Indonesia, this study evaluates a scenario in which Indonesia develops a larger market share of NMC batteries than considered in the Baseline. The market shares of NMC batteries considered in this scenario correspond to those assumed for NMC-leaning regions, such as the European Union and the United States. Compared to the Baseline, this scenario shows a significantly higher demand for nickel, manganese, and cobalt. In the opposite direction, the High LFP Share scenario considers a lower NMC share than in the Baseline, resulting in lower demand for nickel and cobalt. Lithium and graphite demand are negligibly affected by changes in battery technology shares in these scenarios. The High Sodium-Ion Battery Share scenario, meanwhile, shows a lower demand for lithium, cobalt, and graphite and slightly lower demand for nickel. The demand for manganese, in contrast, would increase, due to the assumption that most sodium-ion batteries would use a nickel- and manganese-containing layered oxide cathode.

Demand for battery raw materials in Indonesia can be reduced through policies designed to produce an efficient battery recycling environment, yield smaller passenger vehicle batteries, and slow the increasing demand for private passenger and freight vehicles. Figure 30 displays the impact of these strategies for the Baseline battery technology mix scenario. This analysis projects that implementing a recycling policy as ambitious as in the EU Battery Regulation in Indonesia can reduce the annual demand for lithium, nickel, and cobalt by 1% in 2035 and by 9%–10% in 2050. As described for the other regions, the impacts of this policy gain momentum in the 2040s, when vehicles purchased in the 2020s reach their end of life and yield a substantial stream of recoverable material from recycled batteries. A reduction in the average battery capacities of light-duty BEVs has a more immediate effect on battery raw material demand, which decreases by an additional 32% in both 2035 and 2050. Avoid-and-shift strategies, in contrast, are projected to reduce material demand by additional 6% in 2035 and 9% in 2050. This is mainly because the Avoid-and-Shift scenario assumes LDV sales in 2050 to be only 7% lower than in the Baseline.

Figure 30

Annual raw material demand for lithium, nickel, cobalt, and graphite in Indonesia under the Baseline and demand reduction scenarios



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DOMESTIC RESERVES

Figure A20 in the appendix compares the cumulative demand for lithium, nickel, cobalt, graphite, and manganese with the mineral reserves in Indonesia. According to the U.S. Geological Survey (2024), Indonesia has reserves of nickel and cobalt sufficient to meet the cumulative domestic demand for vehicle electrification beyond 2050. These rich nickel and cobalt reserves present an opportunity for Indonesia to develop an integrated domestic battery supply chain and reap the economic benefits of localizing BEV production.

UNITED STATES

VEHICLE SALES

BEV and PHEV sales shares reflect the Political Momentum scenario from Sen and Miller (2023), which considers numerous vehicle electrification policies and targets in the United States. Prominent among these are the U.S. Environmental Protection Agency (EPA)'s light- and medium-duty vehicle greenhouse gas standards for model years 2027 through 2032 and EPA's Phase 3 HDV GHG draft regulation, released in April 2023 (EPA, 2024). EPA estimates that their final light- and medium-duty vehicle greenhouse gas standards will result in BEVs and PHEVs making up 56% and 13% of new light- and medium-duty vehicle sales in 2032, respectively. Furthermore, this study assumes the United States fulfills its commitment under the *Global Memorandum of Understanding on Zero-Emission Medium- and Heavy-Duty Vehicles* (2021) of achieving 100% ZEV sales by 2040, and assumes this to be solely achieved with BEVs. At the subnational level, the study assumes all Section 177-aligned states adopt California's Advanced Clean Cars II regulation, which phases out the sale of combustion engine LDVs by 2035, and all Section 177 states in discussion to do so adopt the Advanced Clean Trucks rule, which requires 40%–75% of new truck sales to be BEVs by 2035, depending on the vehicle class (Advanced Clean Cars II, 2022; Advanced Clean Trucks Regulation, 2019).[8] BEV and PHEV sales shares that go beyond meeting these policies are not covered.

As displayed in Table 7, the considered policies and targets cumulatively translate into new light-duty BEV and PHEV sales shares of 56% and 13%, respectively, in 2032, which remain constant thereafter. BEV sales shares for new buses and medium- and heavy-duty trucks would reach 100% in 2040.

Table 7
Projected BEV and PHEV sales shares for new vehicle sales in the United States

	2023	2030	2040	2050
Two- and three-wheeler BEV	2%	4%	11%	30%
Light-duty BEV	7%	44%	56%	56%
Light-duty PHEV	2%	9%	13%	13%
Medium-duty BEV	2%	44%	100%	100%
Heavy-duty BEV	2%	34%	100%	100%
Bus BEV	5%	49%	100%	100%

These sales shares are combined with the projected development of total vehicle sales. In the Baseline scenario, the study considers that vehicle sales of all powertrain types will increase only slightly between 2023 and 2050: As presented in Table A2 in the appendix, sales of LDVs increase from 15 million to 16 million, sales of buses increase from 112,000 to 155,000, and MDT and HDT sales collectively increase from 800,000 to 1,100,000. These projections are based on EPA's Motor Vehicle Emission Simulator (MOVE; ICCT, 2022). As a result, the Baseline scenario projects annual BEV and PHEV sales to increase rapidly to 12 million vehicles in 2035 and remain relatively constant thereafter, as pictured in Figure 31 (left). Approximately 93% of BEV and PHEV sales in 2035 are projected to be LDVs.

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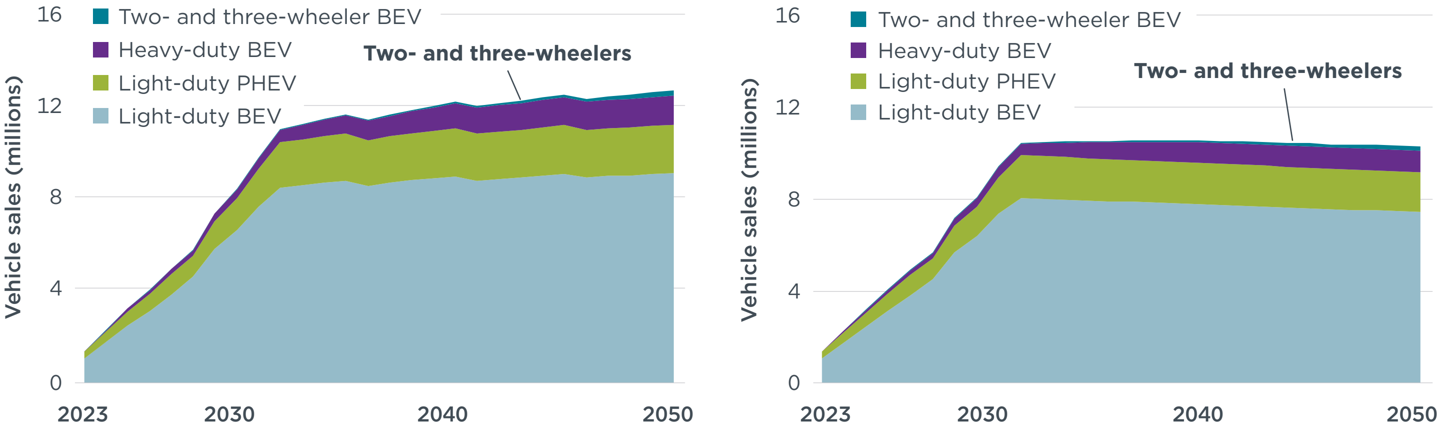
[8] The states that have already adopted the Advanced Clean Cars II rules are New York, Massachusetts, Oregon, Rhode Island, Vermont, Virginia and Washington. States that are considering adopting the rule include Colorado, Connecticut, Maine, New Jersey, New Mexico. States that have already adopted the Advanced Clean Trucks rules are Colorado, Maryland, Massachusetts, New Jersey, New York, Oregon, Washington and Vermont. States that are considering adopting the Advanced Clean Trucks rules include Connecticut, New Mexico, and Maine.

In the Avoid-and-Shift scenario, the BEV and PHEV sales shares are the same as in the Baseline scenario but the total sales change. As shown in Figure 31 (right), BEV and PHEV sales in 2050 are 19% lower than in the Baseline. This decrease is primarily due to 18% lower sales of light-duty passenger vehicles, reflecting a shift of passenger travel from private cars to public transit, walking and biking, carsharing, and two- and three-wheelers, and 31% and 27% lower sales of MDTs and HDTs, respectively, reflecting the considered reduction in vehicle kilometers traveled combined with higher load factors. The assumed changes in passenger vehicle travel activity in the Avoid-and-Shift scenario are detailed in Table A1. Total vehicle sales in the Baseline and Avoid-and-Shift scenarios are listed in Table A2.

Figure 31

Projected annual BEV and PHEV sales in the United States in the Baseline (left) and Avoid-and-Shift scenarios (right), by segment



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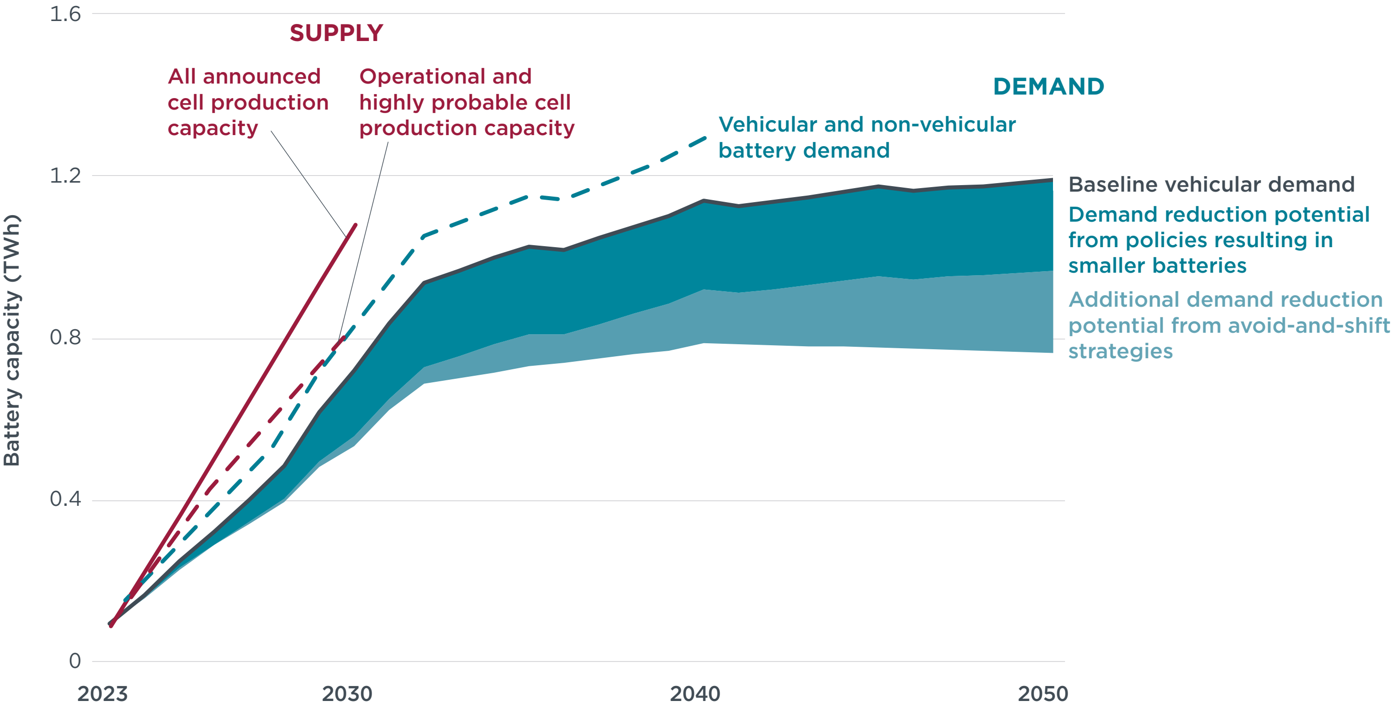
BATTERY DEMAND AND CELL PRODUCTION

Our analysis projects that meeting the policies and targets considered for the on-road transport sector in the United States results in an increase in battery capacity demand for BEVs and PHEVs from 95 GWh in 2023 to 720 GWh in 2030 and 1.1 TWh in 2040, as displayed in Figure 32. Adding BMI (2024b) estimates on non-vehicular battery capacity demand, the total battery capacity demand increases from 134 GWh in 2023 to 823 GWh in 2030 and 1.3 TWh in 2040. In the Baseline scenario, average light-duty BEV battery sizes are conservatively assumed to continue to increase by 10% between 2023 and 2030. The Smaller Batteries scenario, in contrast, shows the projected demand based on the assumption that average light-duty BEV battery sizes would decrease by 20% in the same period. This scenario lowers the annual battery capacity demand for meeting the vehicle electrification targets by 23% in 2030 and by 19% in 2040 compared with the Baseline scenario. The Avoid-and-Shift scenario shows an additional reduction of 4% in 2030 and 14% in 2040.

The total capacity of all announced cell production facilities in the United States, as reported by BMI (2024a), would be 30% higher than the domestic demand from transport and non-transport sectors in 2030. Considering only the proportion of announced cell production capacities of those facilities that are already operational and those that are under construction and considered by BMI to be highly probable to reach the announced capacity, the production capacity still meets domestic battery demand in 2030.

Figure 32

Annual battery demand in the United States by demand reduction scenario compared with announced cell production capacity



Notes: This demand projection excludes lead acid batteries. Cell supply and non-vehicular demand data is sourced from BMI (2024a).

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MATERIAL DEMAND

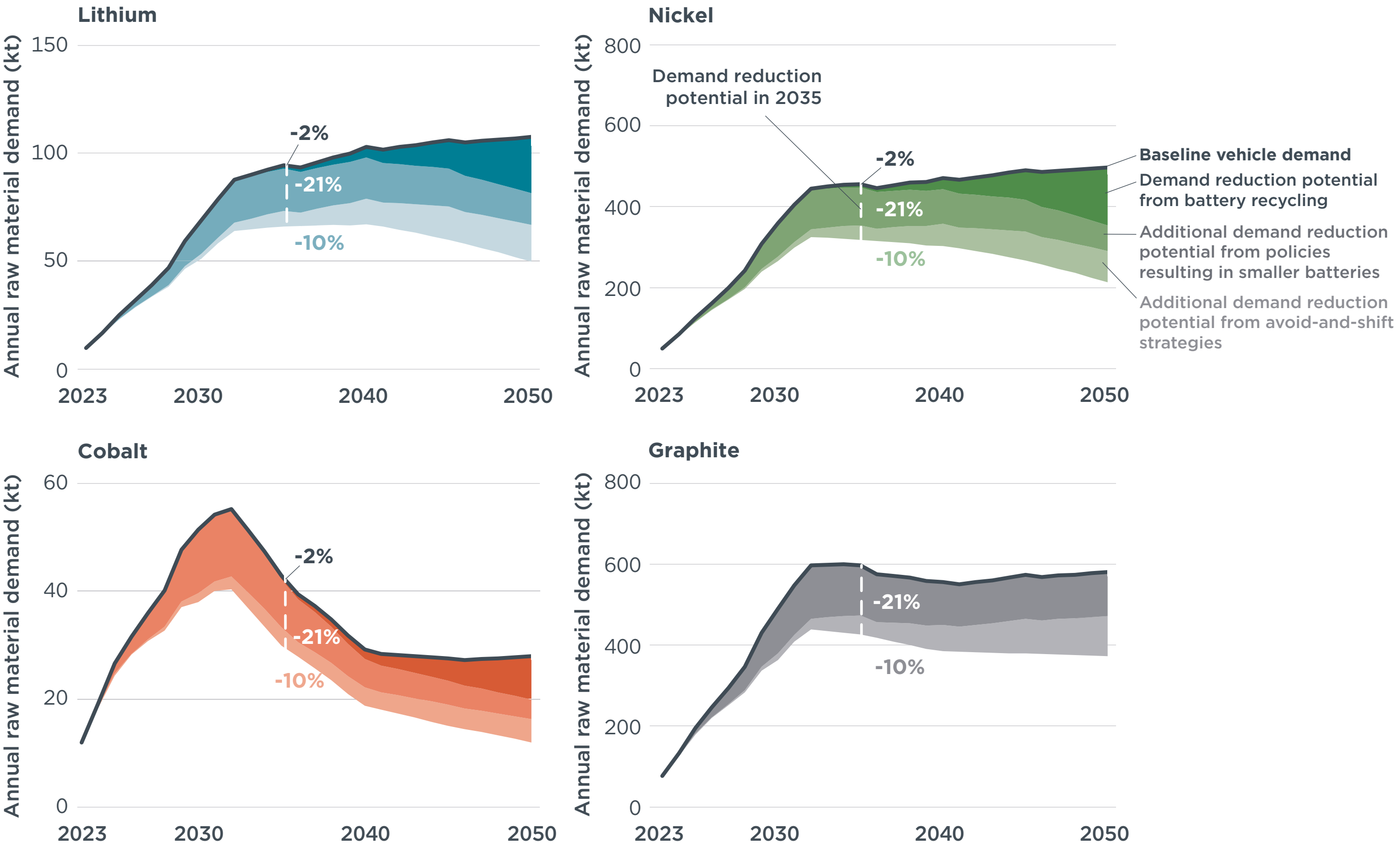
Figure 33 and Figure A22 in the appendix display how the projected battery demand in the Baseline technology mix scenario translates into the raw material demand for lithium, nickel, cobalt, graphite, and manganese. The demand for lithium rises from 10 kt in 2023 to 69 kt in 2030 and 103 kt in 2040. Similarly, nickel demand increases from 50 kt in 2023 to 359 kt in 2030 and 471 kt in 2040, reflecting increasing sales and growing shares of high-nickel, low-cobalt NMC variants within the family of NMC batteries. The demand for cobalt, however, shows a slight increase from 12 kt in 2023 to 51 kt in 2030 but then falls to 29 kt in 2040 due to a shift in NMC variants and an overall decrease in the market share of NMC batteries. The demand for graphite increases steeply from 77 kt in 2023 to 490 kt in 2030 and peaks in 2034 before falling to 557 kt in 2040, after which it remains relatively constant as increasing battery demand is offset by decreasing demand for graphite per kilowatt-hour of battery amid an increase in the share of silicon at the anode.

With a higher share of LFP batteries, as presented in the High LFP Share scenario in Figure A21 in the appendix, the share of NMC batteries decreases, which results in a lower demand for nickel and cobalt. The demand for lithium and graphite, in contrast, is minimally impacted by the share of LFP versus NMC batteries. If sodium-ion batteries replace a part of the LFP share in future, as presented in the High Sodium-Ion Battery Share scenario, the demand for lithium, cobalt, and graphite would decrease significantly. The demand for manganese and nickel, however, would increase in the long term due to the assumption that most sodium-ion batteries would use a nickel- and manganese-containing layered oxide cathode.

Raw material demand can be altered through policy interventions resulting in an efficient battery recycling environment, smaller batteries, and transport demand avoidance and mode shifts. Figure 33 displays the impact of these strategies for the Baseline battery technology mix scenario. Establishing an efficient recycling environment in the United States, such as that foreseen in the EU Battery Regulation, can reduce the annual demand for lithium, nickel, and cobalt by 2% in 2035 and by 24%–29% in 2050. With a reduction in battery sizes, the annual demand for all selected materials decreases by 21% in 2035 and by 18%–19% in 2050, again illustrating the large potential of battery right-sizing for passenger cars for reducing aggregate material demand. Avoid-and-shift strategies could reduce material demand by additional 10% in 2035 and 21%–27% in 2050. As above, the larger reduction from avoid-and-shift strategies in 2050 reflects the time necessary for economic incentives and changes in infrastructure to reduce passenger car and freight transport.

Figure 33

Annual raw material demand for lithium, nickel, cobalt, and graphite in the United States under the Baseline and demand reduction scenarios



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DOMESTIC RESERVES

Figure A23 in the appendix compares the cumulative demand for lithium, nickel, cobalt, graphite, and manganese with mineral reserves in the United States. According to the U.S. Geological Survey (2024), the United States has ample manganese and substantial lithium reserves to meet part of the cumulative domestic demand for vehicles through 2050 under the Baseline scenario. While the reserves are sufficient to meet the cumulative demand for lithium from road transport electrification through between 2030 and 2040, the manganese reserves are sufficient beyond 2050. The US also has small nickel reserves, however if exploited, these wouldn't be sufficient to meet the cumulative domestic nickel demand for vehicles through 2030.

SUMMARY AND CONCLUSIONS

To reduce the climate and air pollution impacts of road transport, a growing number of governments have adopted or proposed policies and targets to support a transition from combustion engine to electric vehicles. This report estimated the demand for battery cell production and raw material supply required to meet policies and targets that have been adopted or are under discussion, covering all segments of road transport: two- and three-wheelers, light-duty vehicles, medium- and heavy-duty trucks, and buses. It calculated global estimates and evaluated the demand in five major vehicle markets (China, the European Union, the United States, India, and Indonesia). This was compared with mineral reserves and announced battery cell production and mineral supply capacities. Given the uncertainty of the battery technology mix in the medium and long term, this study compared a Baseline scenario, which assumed a continuation of current trends, with a scenario modeling a larger increase in the market share of lower-cost LFP batteries and a scenario that assumed that significant shares of the BEV and PHEV market could be based on sodium-ion batteries. Further, the study evaluated how an efficient battery reuse and recycling environment, a reduction in the average battery size for light-duty BEVs, and a change in vehicle sales through avoid-and-shift transport policies could reduce battery raw material demand while maintaining the pace of global road transport electrification.

Key findings of the analysis can be summarized as follows:

Global mineral reserves are more than sufficient to meet battery material demand in the long term. If the global battery demand for road transport through 2050 were to be met only with lithium-ion battery technologies already commercialized today, and if no raw material demand reduction measures were implemented, the accumulated demand would correspond to up to 49% of the current land-based reserves of lithium, 38% for nickel, and 38% for cobalt. These numbers indicate that, even in a conservative estimate, the current mineral reserves would be more than sufficient to meet future demand. Among other implications, these findings indicate that the exploration of deep-sea mining is not needed to meet future battery material demand.

Moreover, new battery technologies with different mineral compositions, such as sodium-ion batteries, may arise and reduce the demand for the materials assessed in this study. Further, mineral reserves are likely to continue to increase. With ongoing exploration of mineral deposits, development of new mining and processing technologies, and fluctuating raw material market prices, global reserves and the portion of known deposits classified as reserves have grown continually over the last decade. For lithium in particular, reserves have grown by a factor of three since 2010, and doubled since 2019 alone.

The scaling up of material supply is expected to keep pace with growing demand. Despite the abundance of reserves of key battery materials in the long term, mineral supply capacities will need to be scaled up to keep pace with the rapid increase in cell production and battery demand in the short and medium term. On a global level, anticipated mining capacities would meet 101% of the annual raw material demand for lithium, 97% of the demand for nickel, and 85% of the demand for cobalt in 2030, including the demand for non-transport and non-battery applications. In a scenario with a higher increase in market shares of LFP batteries, 102% of the demand for lithium, 108% of the demand for nickel and 103% of the demand for cobalt in 2030 would be met. By contrast, in a scenario with considerable market shares of sodium-ion batteries, the demand for lithium would be reduced substantially, allowing the anticipated lithium supply capacities to meet 116% of demand in 2030. These scenarios highlight the fact that the market can react to low supply or high prices of individual materials by switching to higher market shares of battery technologies containing none or less of these materials. This has already been demonstrated by the shift to low-cobalt NMC variants, and by the increasing market share of LFP batteries containing no nickel and cobalt.

Notably, these numbers do not include all announced material supply capacities, but only those that are anticipated to be realized based on factors such as demand projections and commodity prices. When considering the total capacity of announced mines, the supply would be higher. For example, all announced lithium mining capacities for 2030 would correspond to 122% of the projected lithium demand in the Baseline scenario. These additional capacities would be needed to keep pace with the projected material demand after 2030. Given the long and unpredictable lead times for new mines, it is crucial that industry investments continue to flow upstream to maintain growth in battery material mining and processing capacities to meet battery demand. For lithium mines, lead times between initial discovery of the deposit to the start of production are typically shorter than those for other battery minerals, varying between 4 and 7 years (IEA, 2021). In contrast, the average lead time is 13 years for nickel sulfite mines, 20 years for nickel laterite mines, and around 17 years for copper mines (IEA, 2021; IEA, 2023b; Heijlen et al., 2021). As cobalt is typically mined as a byproduct of nickel or copper mining, the lead times of cobalt mines match those of nickel and copper mines.

Despite a general reliance on global material supply chains, domestic reserves can help to meet future demand. Building resilient global supply chains is necessary to meet vehicle electrification policies and targets in all regional markets. However, domestic reserves can partially satisfy the domestic raw material demand. For instance, in China, reserves of lithium are estimated to exceed the cumulative domestic demand from batteries for road transport until between 2040 and 2050, reserves of nickel exceed demand until between 2030 and 2040, and reserves of manganese and natural graphite exceed demand beyond 2050. In the United States, current lithium reserves could meet accumulated demand until between 2030 and 2040, and manganese reserves are two orders of magnitude higher than demand through 2050. The European Union has considerable nickel reserves and smaller lithium reserves. If exploited, nickel reserves in the French overseas territory of New Caledonia would be sufficient to meet the region’s cumulative demand from road transport electrification through between 2040 and 2050. Nickel and cobalt reserves in Indonesia largely exceed domestic demand through 2050, while in India, rich reserves of natural graphite and manganese massively exceed accumulated demand through 2050.

Announced battery cell production capacities exceed future domestic demand in China and the United States, and are close to projected domestic demand in the European Union, while investments in India and Indonesia are not yet on pace with projected domestic demand. On a global level, the capacities of announced battery cell production plants are nearly twice as high as the 2030 combined road transport and non-vehicular battery capacity demand. When counting only the capacity of plants that are already operational and those currently under construction that are classified by BMI as highly probable to reach the announced capacity, the capacities still exceed the 2030 demand. The majority of current and announced cell production capacities are located in China, corresponding to 84% of global capacities in 2023 and 67% in 2030. If all announced cell production capacities in China were realized, they would be more than 3 times larger than domestic demand, including demand from non-vehicular applications. In the United States, total announced cell production capacity would also exceed the battery capacity demand in 2030 while the total announced cell production capacity in the European Union is close to meeting total domestic demand. When considering only facilities that are either already operational and those under construction that are considered highly probable to reach the announced output, capacities in the United States correspond to 103% of domestic demand in 2030, while those in the European Union cover just 72% of road transport and non-vehicular battery capacity demand, highlighting the importance of EU Member States supporting the realization of announced investments. In India and Indonesia, the capacities of announced cell production plants are more limited: By 2030, the capacity of all announced cell production capacities in India corresponds to 49% of the domestic battery demand expected to result from currently discussed policies and targets, while announced cell production capacities in Indonesia cover only 44% of domestic demand.

An increase in battery demand would likely spur more investments in cell production facilities. With lead times of 1–5 years between the completion of initial feasibility studies and the start of production (IEA, 2022), these capacities are expected to be developed on comparatively short timelines.

Reversing the trend of increasing battery sizes for light-duty BEVs is the most immediate way to reduce battery and raw material demand, while battery recycling and avoid-and-shift policies show their full potential in the longer term. As light-duty BEVs make up the largest share of battery demand in the transport sector, reducing their average battery size by 20% compared to today's level would reduce the annual global battery and mineral demand by 28% in 2035 and 27% in 2050 relative to a Baseline scenario in which the average battery size continues to grow by 20% in most markets and by 10% in the United States.

By contrast, this study finds that establishing efficient reuse and recycling policies akin to those in the EU Battery Regulation on a global scale would markedly reduce raw material demand for lithium, nickel, and cobalt after the delay between the production of a vehicle battery and its eventual recycling (and, if applicable, its continued use in a second-life application). In this way, recycling is expected to yield larger benefits beginning in the late 2030s: On a global level, recycling is projected to reduce lithium raw material demand by 1% in 2035 and 16% in 2050, and nickel and cobalt demand by 1% in 2035 and 18% by 2050. A change in vehicle sales due to avoid-and-shift policies is also expected to take time to reach full potential. In addition to recycling and smaller batteries, avoid-and-shift strategies could reduce global battery demand by additional 6% in 2035 and by 17% in 2050. Mineral demand would be reduced by 6%–8% in 2035 and by 17%–25% in 2050, depending on the mineral.

DISCUSSION

The study estimated the future demand for batteries and materials needed to meet current vehicle electrification policies and targets and those under discussion. This section discusses the assumptions and uncertainties inherent to this type of analysis, as well as the limitations of the data considered for the supply side. Select assumptions and results of this study are also compared to those of similar battery material demand estimates in the literature.

LIMITATIONS

This study aimed to account for some uncertainties of future demand estimates by exploring different scenarios (e.g., related to the development of average battery capacities of passenger light-duty BEVs, battery material recycling, and market shares of battery technologies). Nonetheless, not all uncertainties could be addressed in these scenarios. This section discusses certain limitations associated with the assumptions of this analysis.

Vehicle sales

A broad assumption integral to the ICCT Roadmap model's vehicle sales projections is that global vehicle sales will increase alongside population growth and economic development. In particular, the prevalence of private passenger vehicle ownership is expected to keep increasing in developed economies and grow even faster in developing economies. Accordingly, the projected growth in global light-duty passenger vehicle sales (of all powertrain types) almost doubles from 89 million in 2023 to 150 million in 2050. This projection explicitly or implicitly rests on assumptions regarding economic development, land use development patterns, and governments' provision of public transportation options.

Given the uncertainty regarding these assumptions—and to highlight the potential impact of policy interventions—the growth of vehicle sales in the Baseline scenario was compared to an Avoid-and-Shift scenario with less private passenger car transport and on-road freight transport activity. In this scenario, the growth in global light-duty passenger vehicle sales, for instance, was half as much as in the Baseline scenario, amounting to 126 million in 2050. Similarly, the increase in global sales of light commercial vehicles, MDTs, and HDTs would be lower than in the Baseline scenario. As discussed in the methods and data section, the Avoid-and-Shift scenario, developed by the ITF and modified by the ICCT, is based on reduced private passenger car travel activity in urban regions, which is partly compensated by higher passenger travel activity in other modes of passenger transport. This study assumed that the changes in passenger transport activity are proportionally reflected in new vehicle sales, neglecting that the usage intensity of vehicles already on the road could also change. Further, this study assumed that the changes in urban areas apply globally. For both reasons, this assessment likely overestimated the potential effect of avoid-and-shift policies on vehicle sales and thus battery cell production and mineral demand.

Battery capacities

A key assumption in the Baseline scenario is continued growth in the average battery capacity of light-duty BEVs and electric two- and three-wheelers through 2030. This assumption was based on vehicle sales data for 2018–2022 for China, the European Union, and the United States, which indicate growing battery sizes in most vehicle segments and a trend of consumers in major markets purchasing larger vehicles such as SUVs and pickup trucks. Considering that the current trend is motivated by a consumer demand for longer ranges despite higher costs, it was assumed that at some point, the average consumer demand for range will be met and consumers will prefer decreased battery costs. Therefore, average light-duty BEV battery sizes were assumed to remain constant after 2030. However, there is a level of uncertainty over whether this trend will persist and how it will play out in other regions across the world. While this study considered the same future increase in battery size globally, regional specificities may result in an earlier or later saturation in the growth of battery sizes. Additionally, current trends in average battery capacities could be reversed, especially if incentivized by policies. If BEVs were to become more energy efficient, and these improvements would not result in higher ranges but solely be reflected in a reduction of battery size for a given range, the average battery sizes of light-duty BEVs could be decreased. To estimate the impact of such developments, the study compared the Baseline scenario with a Smaller Batteries scenario.

For MDTs, HDTs, and buses, sales of BEVs are much lower than of LDVs. Especially for MDTs and HDTs, the few models that have been commercialized may not be representative of the full range of applications. Hence, except for the more developed electric HDV market in China, the estimation of battery cell and material demand for electrifying the HDV segments was largely based on simulation studies and data for a few markets instead of being based on average characteristics from actual sales numbers. The current average battery sizes in these segments and their future development are thus more uncertain than for the LDV segments. Moreover, the development of MDT and HDT battery sizes after 2030 is highly uncertain. As longer-range trucks electrify and their respective sales shares increase, it is possible that average truck battery sizes increase rather than remain constant, as assumed in this study.

Market shares of battery technologies

This study translated battery capacity demand estimates into material demand based on scenarios for the development of market shares of battery technologies. Any projection of the medium- to long-term development of these market shares is highly uncertain and should be understood as indicative of market trends, rather than a detailed prediction. Only a few years ago, for instance, many analysts expected the market share of LFP batteries to decrease. Instead, due to technological improvements and the motivation to avoid using comparably more expensive nickel and cobalt, LFP batteries became the dominant technology in China and are starting to enter the EU and U.S. markets. Likewise, the potential emergence of sodium-ion batteries, which could significantly reduce the need for lithium and graphite, is highly uncertain. To account for such uncertainties, this analysis evaluated the battery material demand outlook for three scenarios for future battery technology market shares: a Baseline in which the share of LFP batteries continues to moderately increase, a High LFP Share scenario that considers stronger growth in the market shares of LFP batteries, and a High Sodium-Ion Battery Share scenario in which a substantial share of the market would be met with sodium-ion batteries.

Shares of battery technologies in individual markets can significantly differ from global averages. As of today, there appear to be two broad groups of markets: those with above-average NMC shares, such as the European Union, the United States, and Japan, and those with above-average LFP shares, led by China and also including India and Indonesia. This analysis thus employed two aggregated sets of values for the shares of battery technologies in LFP-leaning and NMC-leaning markets. These two sets of battery technology shares are a simplification that may obscure differences within the countries assigned to the two groups.

Reuse and recycling

Estimating the future availability of battery materials from the recycling of end-of-life vehicle batteries depends on many assumptions, including the service life of the battery in the vehicle, potential second-life usage, battery collection rates, and the share of mineral content in a battery that will be recovered in a quality high enough to be reused in battery manufacturing. All of these come with high uncertainties.

While electric vehicle battery recycling is in a nascent state, even in markets with higher PHEV and BEV sales shares, it is unclear what share of electric vehicles will be exported outside of their market of sale, what collection rate for end-of-life vehicle batteries can be expected, and what share of batteries will enter a second-life use before being recycled. These uncertainties were addressed by presenting two extreme scenarios: one without any recycling other than in the European Union and the other with global implementation of the ambitious requirements of the EU Battery Regulation (Tankou et al., 2023a). Details about the assumed collection and reuse rates employed in the recycling scenarios are included in Step 5 of the methods and data section.

Battery and material demand from other applications

When combining estimates of cell and material demand resulting from on-road vehicle electrification policies with the cell and material demand in other applications, this study relied on literature data from BMI and the IEA. As the demand for lithium-ion batteries in non-vehicle applications is below 10% of total demand (BMI, 2024b), the uncertainty concerning these estimates is not expected to have a large impact on our comparison of supply and demand. The material demand for lithium, nickel, and cobalt in non-battery applications, however, may be a significant source of uncertainties. For instance, the 2030 nickel demand for other applications of 3.0 Mt was based on the Advanced Policies Scenario in the IEA's Critical Minerals Data Explorer (IEA, 2024a), but is valued at 2.5 Mt in the IEA's Stated Policies scenario. This gap is large enough to determine whether the Baseline scenario nickel demand would be met by anticipated supply capacities.

Cell production and material supply capacities

On the supply side, this study presented the latest available data on current and announced cell production capacities by BMI (2024a). While some projects may be delayed or canceled, new capacities continue to be announced. For this reason, we consider that announced future production capacities underestimate the actual capacities that will be realized to meet the demand. For the material supply, this analysis generally lacked data on the future development of mining and material refining capacities and only displayed the 2030 global mining capacities as anticipated by IEA (2024b) for most materials. For the more detailed discussion on announced lithium mines, the BMI (2022) data considered in this analysis lack information on 177 out of 330 mines and are dated to December 2022, thus omitting more recent announcements.

Global trade dynamics

Another limitation of this analysis is the omission of how global trade dynamics will influence the availability of raw minerals and battery-grade minerals for cell production in different regions. Though beyond the scope of this study, broadening the geographic distribution of all steps of the battery supply chain, from mining and refining to cathode and anode production and cell manufacturing, can make the global battery supply chain more resilient to disruption and increase the supply of minerals available to different producing countries (IEA, 2023c).

Scope of materials covered

In addition to the five materials evaluated, the electrification of road transport is also expected to lead to increasing vehicle-related demand for copper due to its use in the electric motor and battery. This study does not evaluate the supply and demand for copper, however, due to the relatively limited share of current and projected copper demand accounted for by BEVs and PHEV production. The IEA attributed less than 2% of copper demand to BEVs and PHEVs in 2022, and projects a share of about 12% of demand in 2040 (IEA, 2023a). Although the supply chain for copper is mature and can likely accommodate the growth in demand from BEVs and PHEVs, the mineral is also key to other technologies in the global energy transition, including renewable energy plants and the expansion of the grid. Potential bottlenecks in copper supply may thus depend to a considerable extent on how non-vehicle copper demand evolves over time.

Likewise, this analysis does not project the demand for phosphorous, because battery-related demand makes up a small proportion of total phosphorous demand. Phosphorous is mainly used in agriculture as a fertilizer. The IEA estimates that if all batteries today used LFP cathodes, they would correspond to about 1% of current agricultural phosphorous demand (2023a). Although BEV and PHEV battery demand makes up a small share of global phosphorous demand today, as battery demand grows, phosphorous demand for LFP cathodes could conflict with demand from other sectors.

COMPARISON WITH LITERATURE

The results of our analysis add to a growing body of literature that has estimated future demand for BEV and PHEV batteries.

Global estimates

The Announced Pledges scenario in the IEA's *Global EV Outlook 2024* projected global BEV and PHEV sales in 2030 similar to those projected in the Political Momentum scenario modeled in this study (IEA, 2024c). The IEA also projected similar battery demand in 2030 for all on-road vehicle segments, at about 3.9 TWh, compared to 3.8 TWh in this analysis. Moreover, the regional distribution of battery demand in 2030 closely matches that found in this study.

BNEF's *Electric Vehicle Outlook 2023* projected passenger BEV and PHEV sales globally in 2035 to be slightly lower than this study's projections, resulting in a lower estimate of global battery demand for LDVs in 2035 of about 4.3 TWh, compared with this analysis's estimate of 5.0 TWh (BNEF, 2023). This difference can also partly be attributed to this analysis's assumption that passenger BEV battery sizes will increase by 20% in most markets and 10% in the United States between 2023 and 2030, while BNEF's Growth scenario included a 5% growth in range, for which the change in battery size was unspecified.

Finally, this study projected global battery demand from vehicle electrification in 2040 to approach 7.0 TWh, which is similar to the SSP1 scenario in a 2023 study by Fraunhofer IZM and ISI (Maisel, 2023b) that estimated battery cell demand from all on-road vehicle segments globally in 2040 at 6.7 TWh. The difference in battery demand can be attributed to different BEV uptake timelines between the SSP1 sustainable development scenario and the scenario modeled in this study.

European Union

A 2023 Transport & Environment study estimated passenger light-duty vehicles and buses in the European Union would require about 1.0 TWh of battery demand in 2030 and about 1.2 TWh in 2040 (Transport & Environment, 2023). This estimate is higher than this study's estimate for 2030 (0.6 TWh) and slightly lower for 2040 (1.4 TWh). Their higher battery demand estimate in 2030 is due to a more ambitious rate of vehicle electrification considered for passenger vehicles (80% BEV in 2030) compared to that used in this study (54% BEV in 2030), combined with different assumptions about the growth in average battery sizes in passenger vehicles.

United States

An ICCT study by Shen et al. (2024) estimated a battery capacity demand of 650 GWh for light-duty BEVs in the United States in 2030, compared to 620 GWh in this study. The BEV uptake in Shen et al.'s study was based on modeling in EPA's proposed rule for multipollutant standards and assumed BEV and PHEV sales shares would increase to 67% and 7%, respectively, of new LDVs by 2032. Modeling in EPA's final rule, considered in this analysis, estimated that 56% of new LDV sales would be battery electric and 13% would be plug-in hybrids. Moreover, based on modeling by the California Air Resources Board, Shen et al. assumed that light-duty BEV battery capacities would decrease by almost 30% between 2023 and 2030 for a given electric range, while the Baseline scenario in this study assumed that, due to longer ranges and increasing market shares of BEVs in larger vehicle segments, the fleet average battery capacity would increase by 10% in that period. The decrease in the average battery capacity of light-duty BEVs by 20% in the Smaller Batteries scenario of this study, however, is comparable to assumptions of Shen et al.

POLICY IMPLICATIONS

The results of this study suggest that, on a global level, currently announced cell production and mineral supply capacities are likely sufficient to meet the demand resulting from adopted and currently discussed vehicle electrification policies and targets in the short and medium term, and known reserves can meet demand in the longer term. However, existing and announced mining, refining, and battery cell production capacities are concentrated in a few countries. For mining and processing capacities, this generally means that international supply chains would need to be scaled up and strengthened, although a part of future mineral demand could also be met by leveraging domestic mineral resources. For cell production capacities, this means that more investments in domestic capacities would be needed for most countries to become self-sufficient.

Moreover, although not required to implement the vehicle electrification policies considered in this study, lowering the demand for battery raw material mining and processing will be critical to improving the environmental benefits of BEVs in comparison with combustion engine vehicles. In other words, the mineral efficiency of BEVs in terms of raw material mined per kilometer driven can be improved. Of the market development scenarios examined in this study, reversing the current trend of increasing light-duty BEV battery sizes has the largest and most immediate effect on reducing raw material demand. This would also advance purchase price parity of BEVs with combustion engine vehicles. Establishing an efficient battery reuse and recycling environment would also have a large impact on raw material demand but only in the long term, once a high number of electric vehicle batteries reach their end of life. Similarly, avoid-and-shift strategies yield their greatest benefits after measures like financial incentives and the development of shared and active transport infrastructure have had time to reduce passenger car and freight transport activity. Thus, over a longer time horizon, the largest reductions in demand for new raw material mining can be achieved by following all three strategies in parallel.

The policy implications of these findings for creating domestic manufacturing capacities and resilient supply chains and for reducing demand in new raw material mining are presented below.

DOMESTIC MANUFACTURING AND RESILIENT SUPPLY CHAINS

Various policy measures can be put in place to help foster domestic cell and electric vehicle manufacturing and strengthen domestic material mining and refining capacities. As a first step, policymakers can provide more planning security for industry investments by enacting policies with reliable pathways towards increased BEV adoption across all segments of road transport.

Domestic battery component and cell production can be supported through financial incentives linked to battery production, such as the battery manufacturer tax credits in the U.S. Inflation Reduction Act (IRA) or support to be provided under the European Union’s announced Battery Fund, and by tying purchase incentives for electric vehicles to domestic component provisions, such as in the vehicle purchase tax credits in the IRA, purchase subsidies under India’s Faster Adoption & Manufacturing of Electric Vehicles (FAME) scheme, and Indonesia’s program of reduced value-added tax rates for electric vehicles.

For the material supply chain, it is important for capital investments in the electric vehicle supply chain to flow upstream to expand mining and refining capacity. Governments of countries with domestic reserves can provide financial incentives to bring new mines and refining facilities on line. For example, the IRA’s electric vehicle purchase tax credits require that a share of the materials used in the batteries be mined, refined, or recycled in the United States or in a country with which the United States has a Free Trade Agreement or Critical Minerals Agreement (Shen et al., 2024). Several government programs also provide fiscal incentives to mining projects directly, such as under Brazil's Strategic Minerals Investment Fund or Canada's Critical Minerals Infrastructure Fund. Domestic supply chains can be further strengthened through production capacity targets, such as those in the European Union's Critical Raw Materials Act, which sets targets for achieving a specific percentage of mineral mining and refining from domestic sources and includes provisions to diversify the supply of minerals originating outside of the European Union. Further domestic raw material supply can come from investments in innovative mineral recovery technologies such as re-mining tailings from existing mines. For material demand not covered by domestic reserves, securing mineral supplies may require policymakers to negotiate strategic trade agreements with mineral producing countries. Further, cross industry-collaboration, public and private partnerships, and coordination between mineral producer and consumer countries can help coordinate investment opportunities for upstream supply chain activities.

Moreover, although this analysis does not evaluate how mineral refining and chemical processing capacity compare with battery-grade mineral demand, it is highly likely that additional mineral refining capacity will also be needed to meet the projected growing demand for battery-grade minerals. The IEA estimates that the development of mineral refining facilities from feasibility studies to the start of production lasts between 3 to 8 years (IEA, 2022). The growth and geographic distribution of mineral refining capacity is an important topic for further study.

The environmental and social impact of material mining, refining, and battery manufacturing could be improved through the adoption of due diligence standards related to environmental and social risks along the value chain, implementing battery production carbon footprint regulations, supporting local environmental regulations and social standards, and tying public financial incentives to environmental and social criteria. Developing refining capacity near mining sites can help countries with mineral reserves retain a higher share of the economic benefits of the mineral supply chain and reduce the environmental impact of transporting raw minerals.

BATTERY TECHNOLOGIES

As examined in this study, the market shares of different battery technologies largely determine the demand for individual materials. Governments can support the development of battery technologies based on more abundant materials, such as sodium-ion batteries, and technologies based on raw materials with a lower environmental impact by funding fundamental and applied research. Further, by establishing high standards on the durability of electric vehicle batteries, governments can better ensure that batteries do not need to be replaced during their use in BEVs and PHEVs, and that they are available for a longer use in second-life applications, such as stationary energy storage for private households, industry, or the power grid. The longer the lifetime of the batteries, the lower the demand for new batteries produced only for this purpose. On an economy-wide level, more durable vehicle batteries can thereby contribute to a lower demand for battery materials from other applications.

SMALLER BATTERIES

This analysis found that policies resulting in a reduction of fleetwide average vehicle battery sizes of light-duty BEVs generates the most immediate reduction in raw material demand. As a starting point, governments could inform consumers what battery sizes and ranges are best suited for their travel behavior by providing information on charging needs, vehicle energy consumption, and total cost of ownership (Poupinha & Dornoff, 2024). Increased provision of dense and fast-charging networks can also mitigate consumer range anxiety, lowering demand for longer-range vehicles. Further, governments could tie purchase incentives to vehicle size, weight, battery capacity, or to the material intensity of batteries. On a fleet level, reductions in the average size of vehicle batteries could be incentivized by the introduction of corporate average vehicle energy efficiency standards, as efficiency gains enable vehicles to meet consumers' desired range with smaller batteries. In any case, policies incentivizing the production of more energy efficient cars with smaller batteries can translate to consumer benefits of more affordable BEVs with lower operational costs.

BATTERY RECYCLING

Comprehensive regulatory frameworks on recycling, such as the European Union's Battery Regulation, include key principles such as extended producer responsibility provisions for the collection and handling of end-of-life vehicle batteries, mineral-specific recovery rates during recycling, and recycled content requirements in the production of new batteries. Recovery rate provisions can ensure key materials are recovered even if their recovery is not economical. Recycled content targets for new batteries can also avoid downcycling by ensuring materials are recovered with battery-grade purity. Further, battery passport initiatives like those in the EU Battery Regulation require manufacturers to track and disclose information on batteries throughout their lifetime, including on the battery's state of health. These provisions facilitate battery reuse in other applications, as they allow a more efficient assignment of reuse applications. In parallel, financial incentives for battery recycling plants, such as those provided in the IRA, support the scaling up of capacities.

AVOID AND SHIFT

For passenger transport, a coordinated mix of policies from local, regional, and national governments can lower the sales of private passenger cars by implementing strategies to avoid transport demand and by encouraging individuals to shift trips to walking, biking, and public transport. Denser, mixed-use urban areas put residents in proximity to jobs and essential services, enabling them to lower their overall distances travelled (ITF, 2023). Cities centered around well-connected public transport, safe walking and biking infrastructure, and access to on-demand and shared vehicles can give residents access to numerous alternatives to private passenger cars. Combined with investment in multimodal transportation, policies to discourage private motorized vehicles such as congestion charges and parking control can substantially increase the use of walking, biking, and public transport (Kuss & Nicholas, 2022). Certain city-level policies can also disincentivize private automobile travel while lowering vehicle sizes. For instance, a surcharge parking fee for heavier vehicles in Paris, France, charges triple the hourly rate for vehicles above a certain mass, with higher mass limits for BEVs than internal combustion engine vehicles and PHEVs (Chrisafis, 2024).

With regard to freight transportation, demand avoidance strategies can include increasing vehicle load capacities to increase fleetwide efficiency, which is reflected in higher load factors and lower on-road fleetwide vehicle kilometers traveled. Measures to optimize freight efficiency can involve system-wide improvements to road freight logistics, such as the use of GPS technology to optimize routing, asset sharing systems allowing multiple operators to share vehicles, and pricing mechanisms that incentivize operators to maximize load capacities. Urban freight trips are comparatively easier to decarbonize and shift away from private trucks than non-urban freight: Urban deliveries can often be shifted to smaller vehicle modes, such as cargo bikes and light electric vehicles, while long-distance freight can be shifted to rail (ITF, 2023). Moreover, fiscal policies including congestion charges, road tolls, and energy taxation can help improve system-wide freight efficiency.

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APPENDIX

METHODS AND DATA

Table A1

Relative difference in passenger travel activity (in passenger-km per capita) in 2050 by mode of passenger car transport and region between the ITF Baseline and ICCT Shift scenarios

	Combined car-related transport modes	Taxi	Ride-share	Car-share	Private passenger car
Global	-10%	-17%	+60%	+44%	-26%
China	-3%	-1%	+78%	+40%	-39%
European Union	-36%	+16%	+79%	+16%	-45%
India	-33%	-33%	+8%	-8%	-39%
Indonesia	-16%	-21%	+525%	+0%	-32%
United States	-18%	+15%	+124%	+55%	-25%

Table A2

Vehicle sales (all powertrain types) in 2023 Baseline scenario and in 2050 in the Baseline and Avoid-and-Shift scenarios, by segment and regions

Region	Vehicle segment	2023 sales	2050 sales		
		Baseline scenario	Baseline scenario	Avoid-and-Shift scenario	Difference
Global	Two- and three-wheeler	78,846,331	122,247,050	122,247,050	0%
	Light-duty passenger vehicle	77,682,242	135,379,072	117,593,635	-13%
	Bus	1,231,933	2,619,025	2,619,025	0%
	Light commercial vehicle	11,632,250	14,307,655	8,784,107	-39%
	MDT	2,499,470	5,105,041	3,542,408	-31%
	HDT	1,913,634	3,971,880	2,928,808	-26%
China	Two- and three-wheeler	42,886,062	60,593,132	60,593,132	0%
	Light-duty passenger vehicles	22,160,475	42,455,568	41,301,623	-3%
	Bus	170,573	701,154	701,154	0%
	Light commercial vehicle	2,971,000	4,168,347	1,054,709	-75%
	MDT	703,519	1,968,674	1,018,950	-48%
	HDT	441,211	1,156,862	606,113	-48%
European Union	Two- and three-wheeler	1,041,926	55,663	55,663	0%
	Light-duty passenger vehicle	10,990,084	18,110,257	12,797,838	-29%
	Bus	32,142	60,953	60,953	0%
	Light commercial vehicle	1,730,203	2,379,927	1,632,581	-31%
	MDT	50,364	69,405	46,010	-34%
	HDT	250,824	388,934	281,983	-27%
India	Two- and three-wheeler	14,641,966	23,529,851	23,529,851	0%
	Light-duty passenger vehicle	3,256,429	6,248,722	4,915,743	-21%
	Bus	41,358	133,086	133,086	0%
	Light commercial vehicle	466,802	935,213	947,971	+1%
	MDT	70,174	108,568	53,289	-51%
	HDT	205,167	381,528	259,422	-32%
Indonesia	Two- and three-wheelers	3,952,457	5,941,745	5,941,745	0%
	Light-duty passenger vehicle	743,836	3,694,346	3,440,946	-7%
	Bus	4,013	10,548	10,548	0%
	Light commercial vehicle	205,393	154,695	82,543	-47%
	MDT	70,645	190,265	103,426	-46%
	HDT	30,475	114,558	78,745	-31%
United States	Two- and three-wheeler	524,065	699,940	699,940	0%
	Light-duty passenger vehicle	14,084,849	15,534,266	12,679,818	-18%
	Bus	112,427	155,477	155,477	0%
	Light commercial vehicle	733,128	666,369	513,456	-23%
	MDT	562,162	812,307	559,353	-31%
	HDT	245,167	297,102	218,054	-27%

Table A3

Sales-weighted average battery capacity in 2023 and 2030 in the Baseline scenario, by segment and region

Region	Vehicle segment	Average capacity in 2023 (kWh)	Average capacity in 2030 (kWh)	% change
China	**Two- and three-wheeler**	3.0	3.6	+20%
	Light-duty BEV	56	68	+20%
	Light-duty PHEV	24	29	+20%
	MDT	139	161	+16%
	HDT	326	564	+73%
	Bus	213	213	0%
European Union	**Two- and three-wheeler**	3.0	3.6	+20%
	Light-duty BEV	65	78	+20%
	Light-duty PHEV	16	19	+20%
	MDT	132	170	+29%
	HDT	724	545	-25%
	Bus	250	223	-11%
India	**Two- and three-wheeler**	3.0	3.6	+20%
	Light-duty BEV	34	41	+20%
	Light-duty PHEV	21	24	+20%
	MDT	113	100	-13%
	HDT	236	190	-19%
	Bus	213	213	0%
Indonesia	**Two- and three-wheeler**	3.0	3.6	+20%
	Light-duty BEV	59	71	+20%
	Light-duty PHEV	18	22	+20%
	MDT	139	161	+16%
	HDT	326	564	+73%
	Bus	213	213	0%
United States	**Two- and three-wheeler**	3.0	3.6	+20%
	Light-duty BEV	82	90	+10%
	Light-duty PHEV	17	20	+20%
	MDT	160	152	-5%
	HDT	546	583	+7%
	Bus	250	223	-11%
Global	**Two- and three-wheeler**	3.0	3.6	+20%
	Light-duty BEV	62	75	+20%
	Light-duty PHEV	21	26	+20%
	MDT	139	161	+16%
	HDT	326	564	+73%
	Bus	213	213	0%

Figure A1

Projected shares of battery technologies in the BEV and PHEV market in the NMC-leaning (top) and the LFP-leaning group of countries (middle) and in the global average (bottom) in the High LFP Share scenario

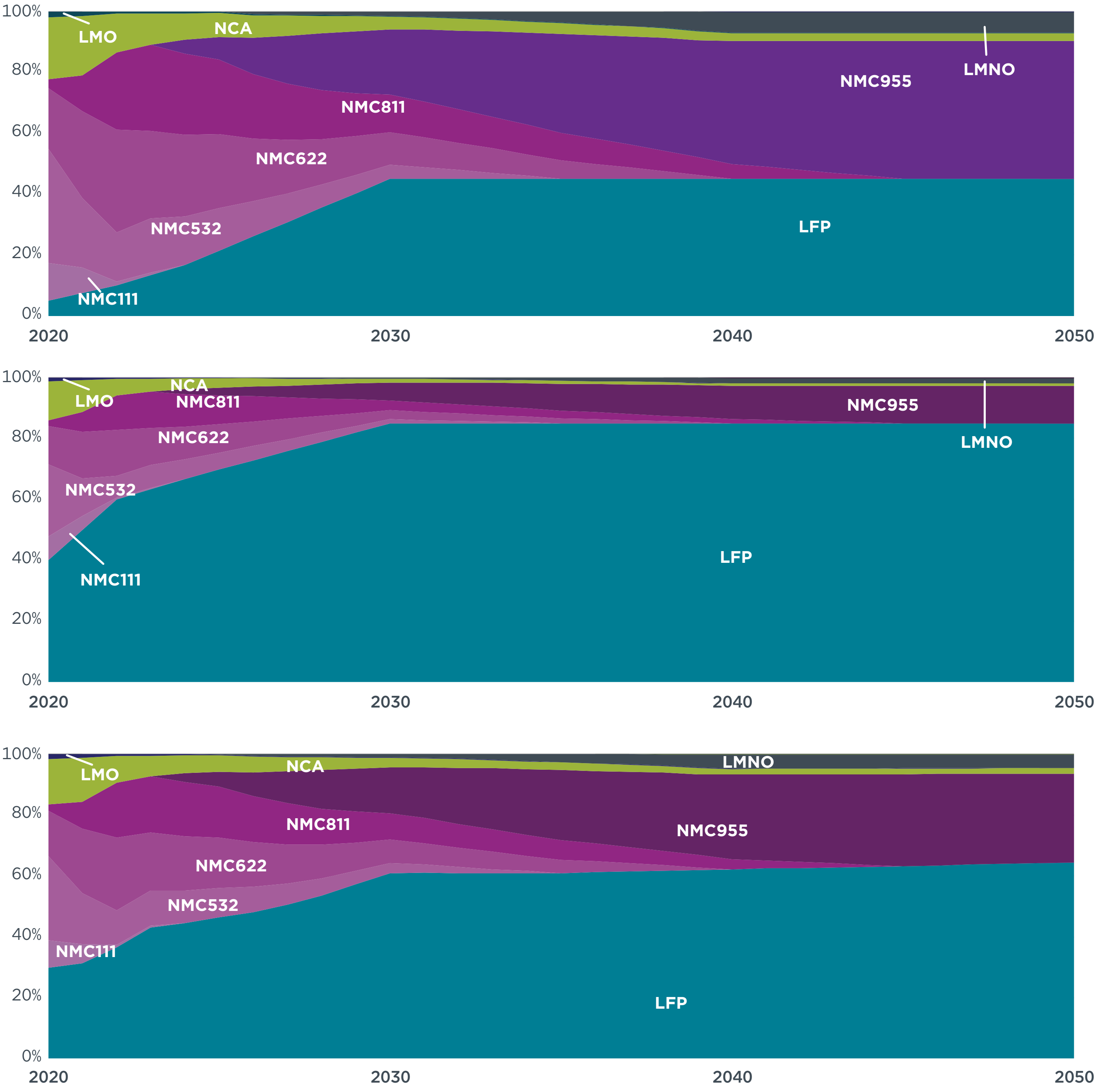

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Figure A2

Projected shares of battery technologies in the BEV and PHEV market in the NMC-leaning (top) and LFP-leaning (middle) group of countries and in the global average (bottom) in the High Sodium-Ion Battery Share scenario

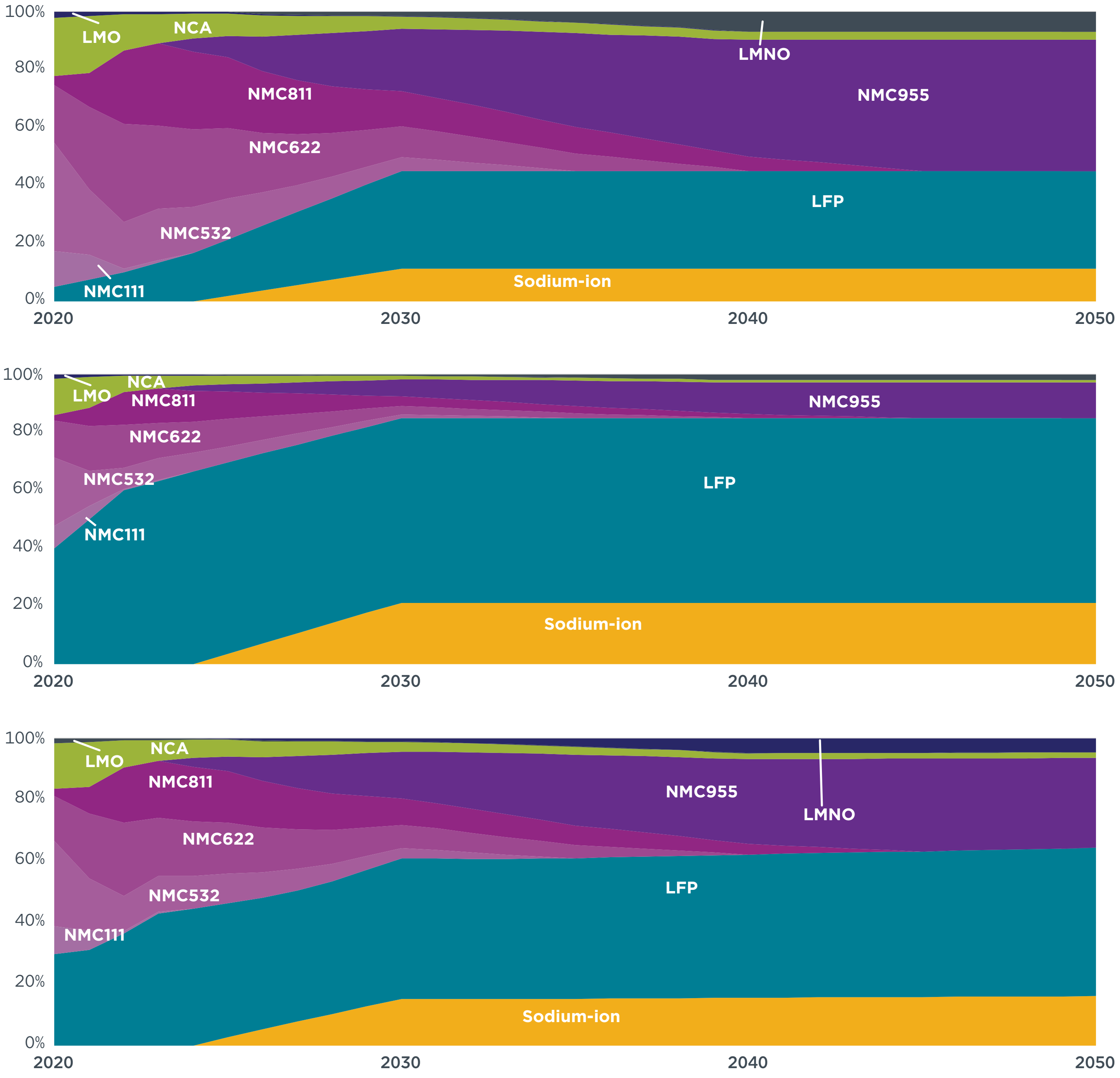

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Table A4

Material demand at the anode and at the cathode in kilograms per kilowatt-hour of battery capacity, by anode and cathode technologies

		LFP	LMO	LMNO	NMC111	NMC532	NMC622	NMC811	NMC955	NCA
Cathode	Lithium	0.08	0.08	0.08	0.11	0.10	0.10	0.09	0.09	0.10
	Nickel			0.34	0.32	0.45	0.52	0.61	0.82	0.66
	Manganese		1.37	0.97	0.33	0.27	0.18	0.08	0.04	0.00
	Cobalt				0.32	0.18	0.17	0.08	0.04	0.13
	Iron	0.68								
	Phosphorous	0.38								
Anode (0% Si)	Graphite	1.00	0.85	0.85	0.90	0.90	0.90	0.90	0.90	0.90
	Silicon									
Anode (2% Si)	Graphite	0.84	0.71	0.71	0.75	0.75	0.75	0.75	0.75	0.75
	Silicon	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
Anode (10% Si)	Graphite	0.48	0.41	0.41	0.43	0.43	0.43	0.43	0.43	0.43
	Silicon	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

RESULTS

Figure A3

Annual global raw material demand for manganese under the Baseline and alternative battery technology mix scenarios

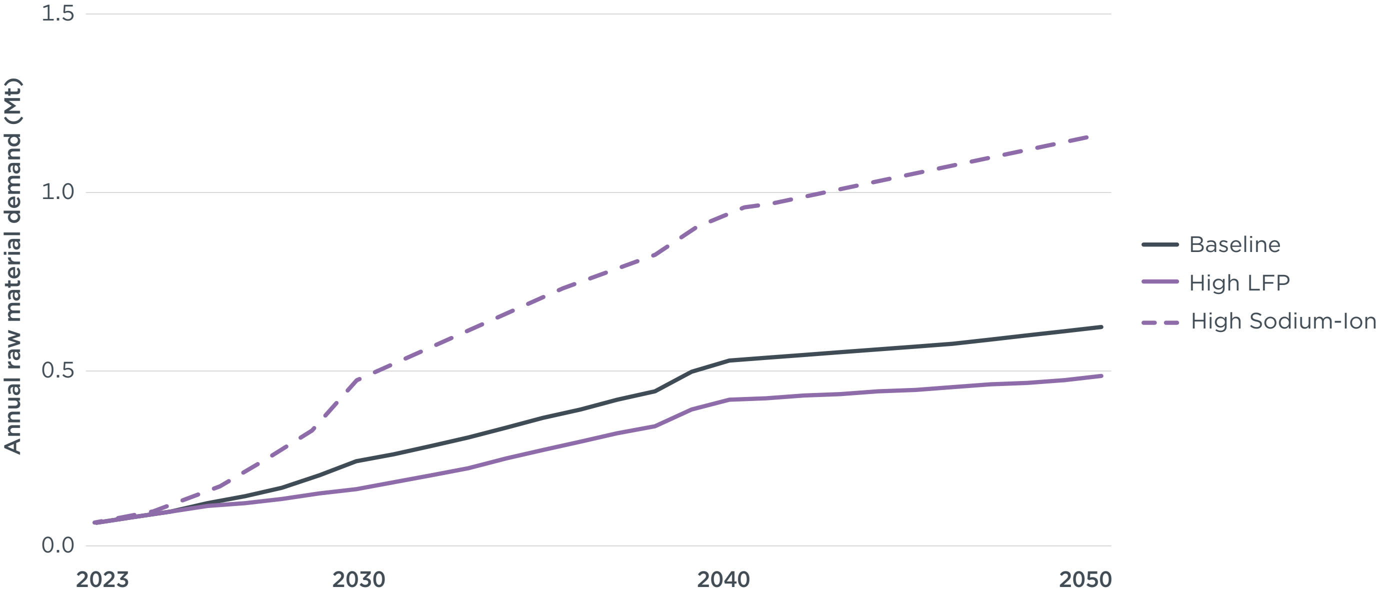

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Figure A4

Annual global raw material demand for lithium, nickel, cobalt, graphite, and manganese under the Baseline and alternative battery technology mix scenarios, in the Smaller Batteries scenario

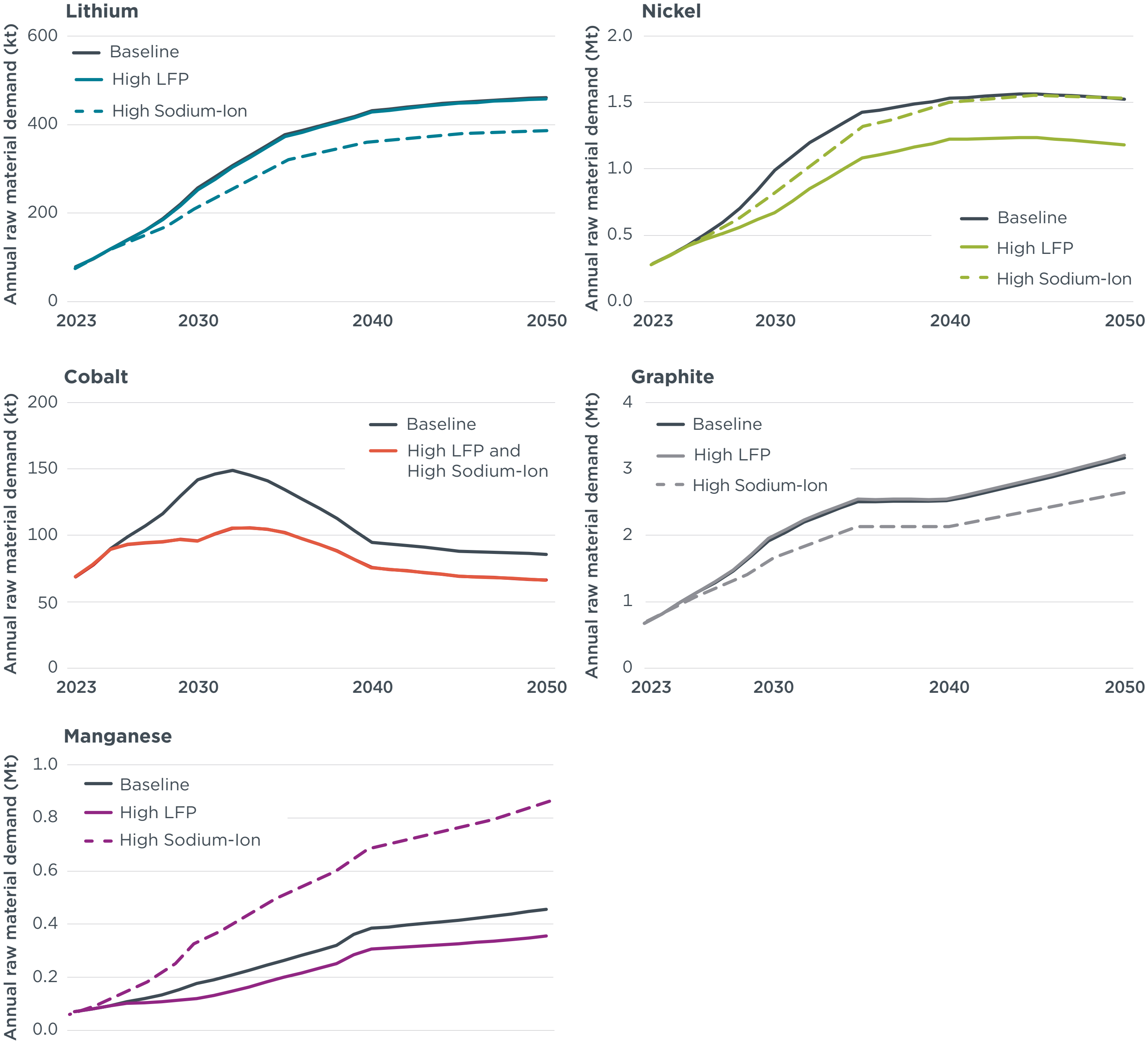

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Figure A5

Annual global raw material demand for lithium, nickel, cobalt, graphite, and manganese under the Baseline and alternative battery technology mix scenarios, in the Avoid-and-Shift scenario

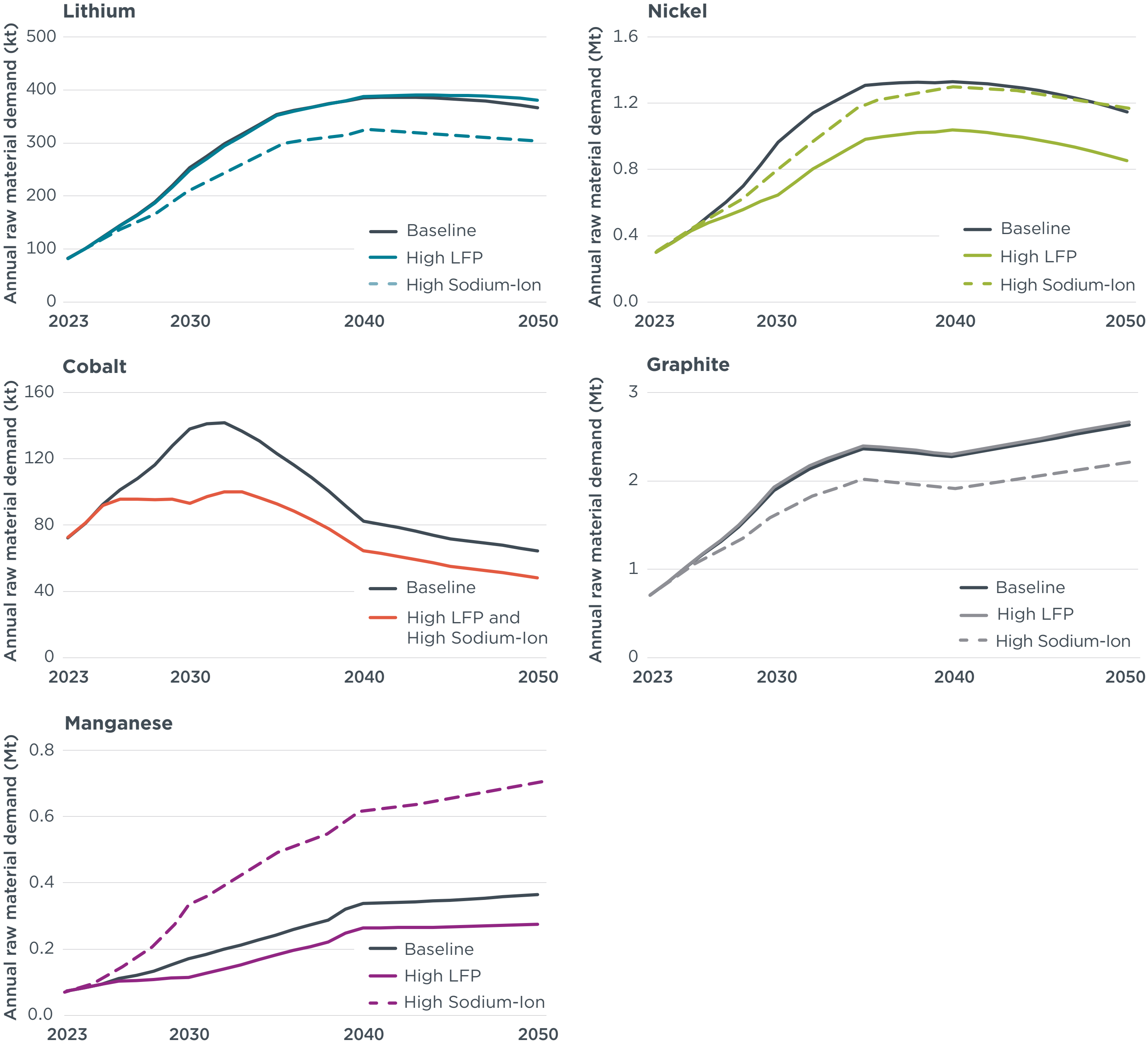

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Figure A6

Annual global raw material demand for manganese under the Baseline and demand reduction scenarios

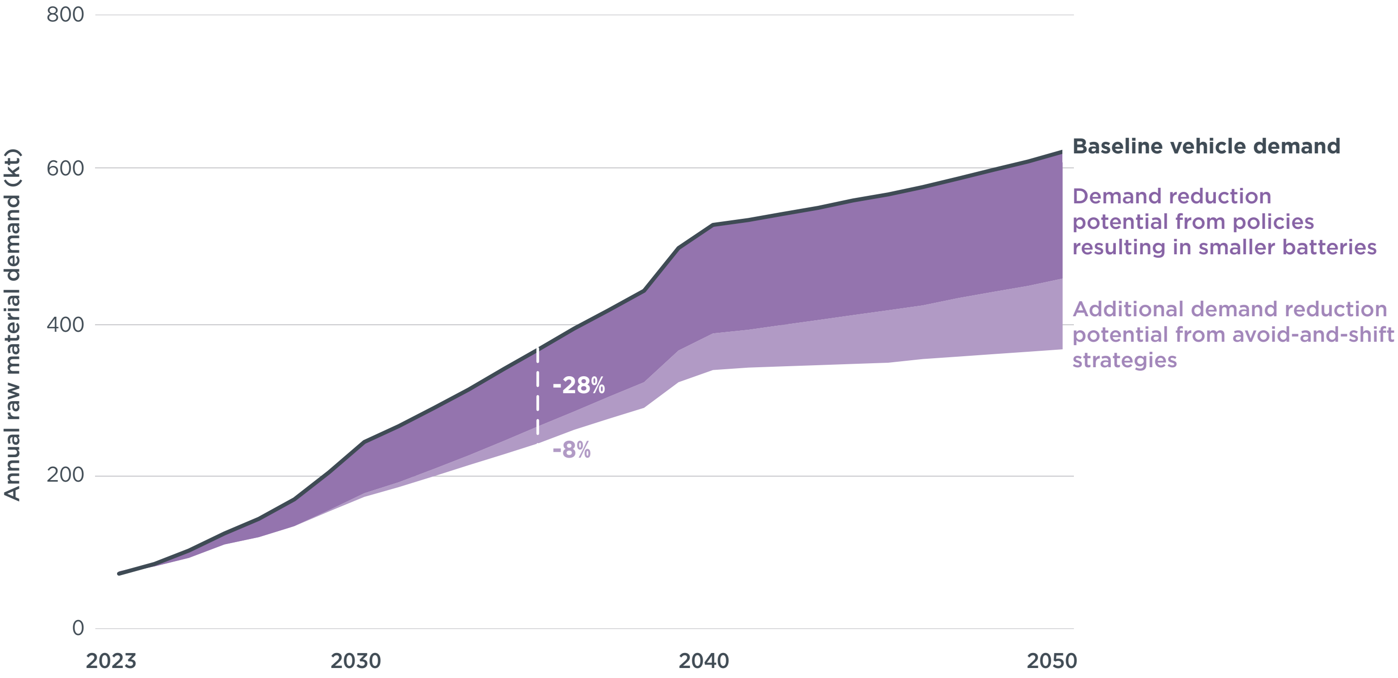

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Figure A7

Annual global raw material demand in 2030 under the High Sodium-Ion Battery Share scenario for lithium, cobalt, and nickel by battery demand reduction scenario compared with anticipated supply capacity

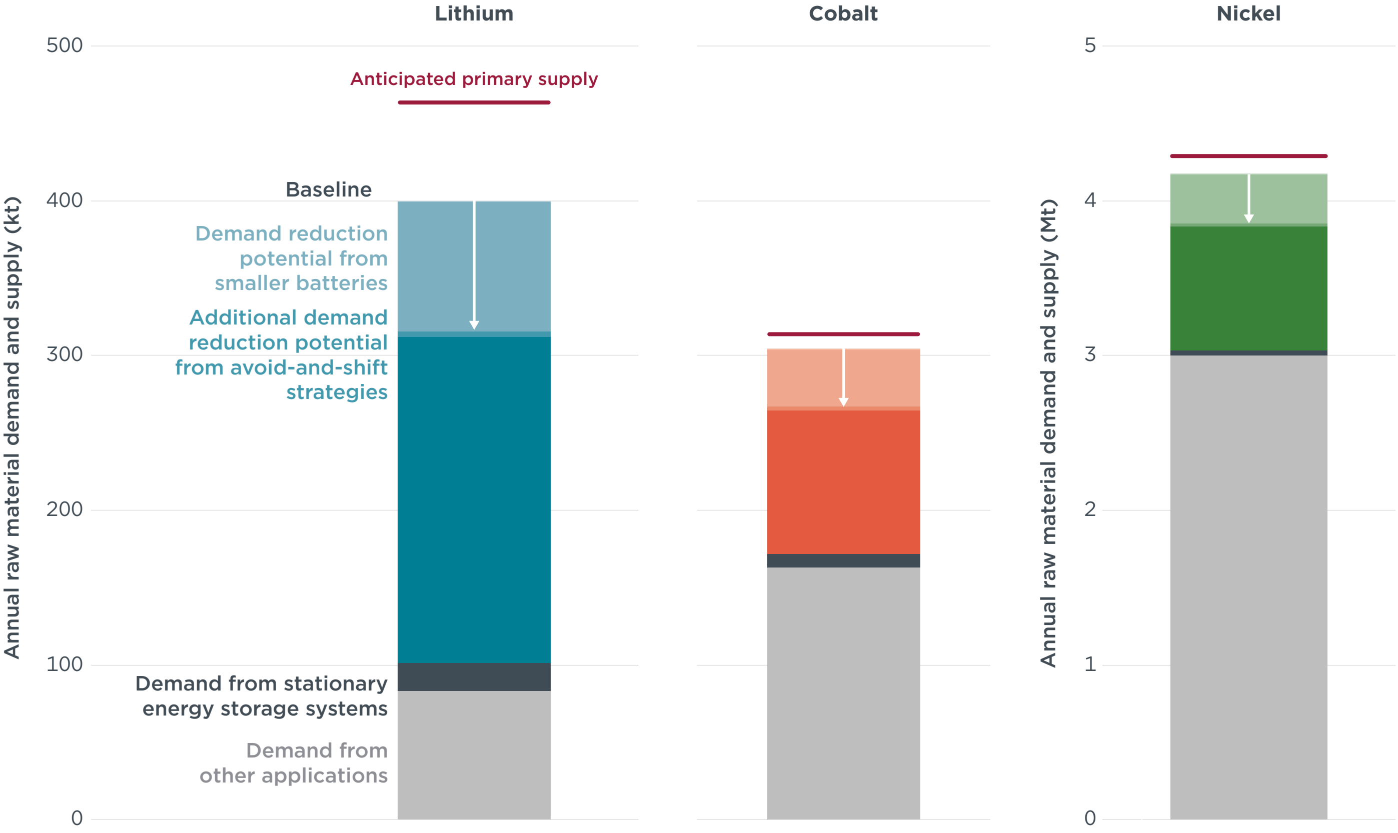

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Figure A8

Cumulative raw material demand until 2050 as a share of global reserves in the High Sodium-Ion Battery Share scenario

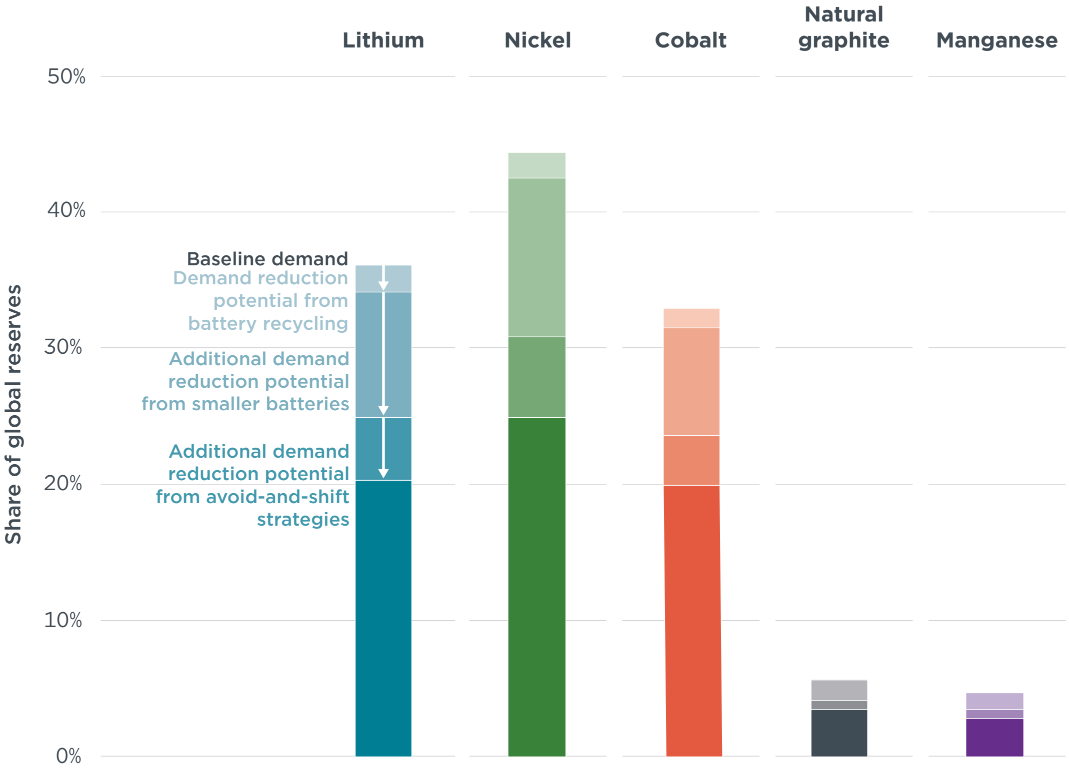

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Figure A9

Annual raw material demand for lithium, nickel, cobalt, graphite, and manganese in China under the Baseline and alternative battery technology mix scenarios

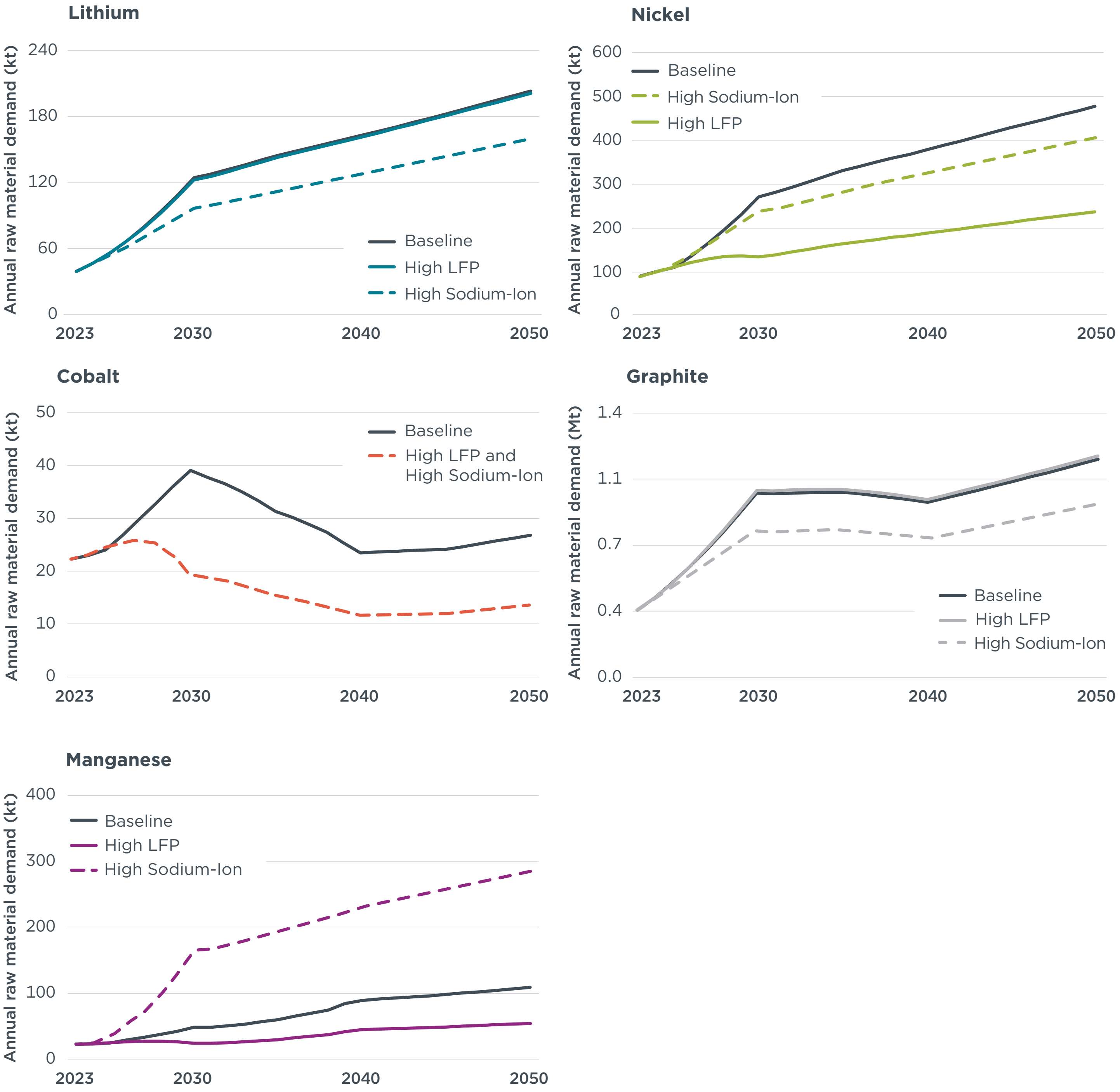

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Figure A10

Annual raw material demand for manganese in China under the Baseline and demand reduction scenarios

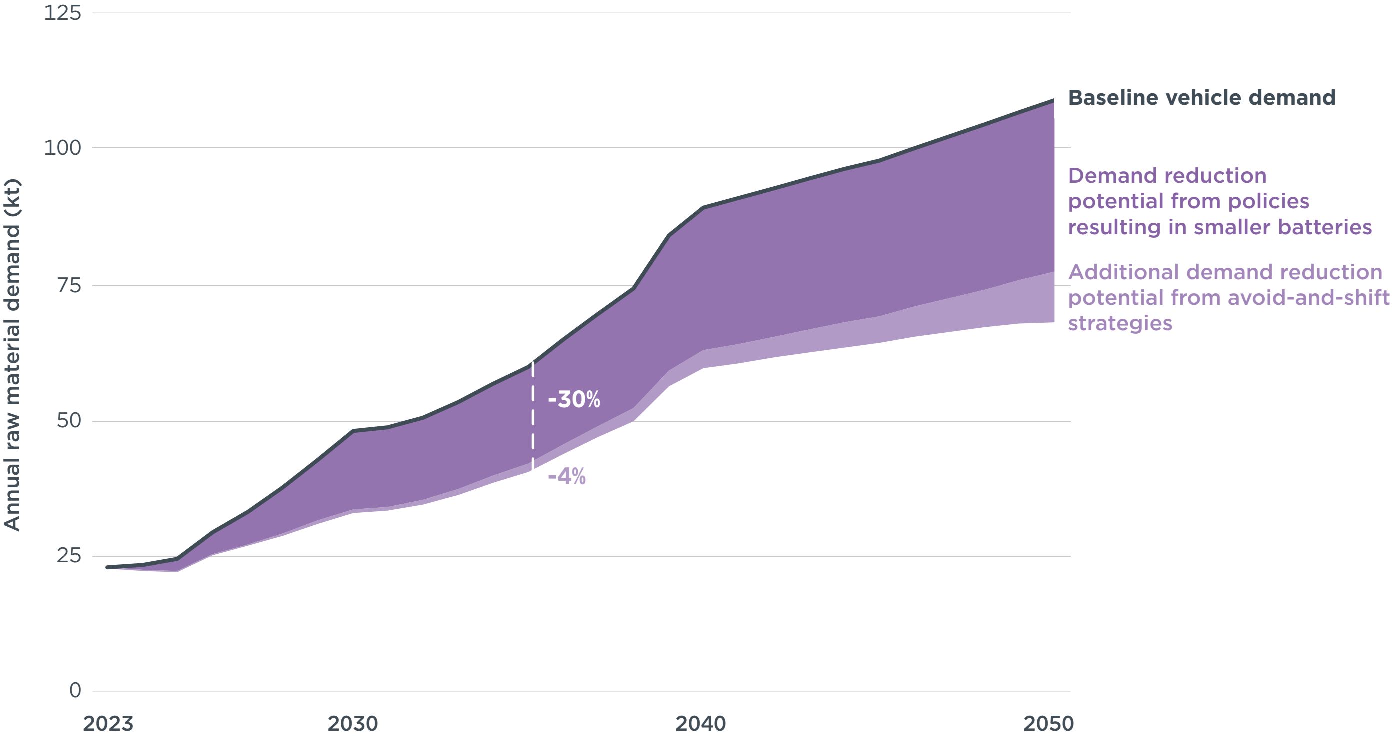

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Figure A11

Cumulative raw material demand and reserves in China

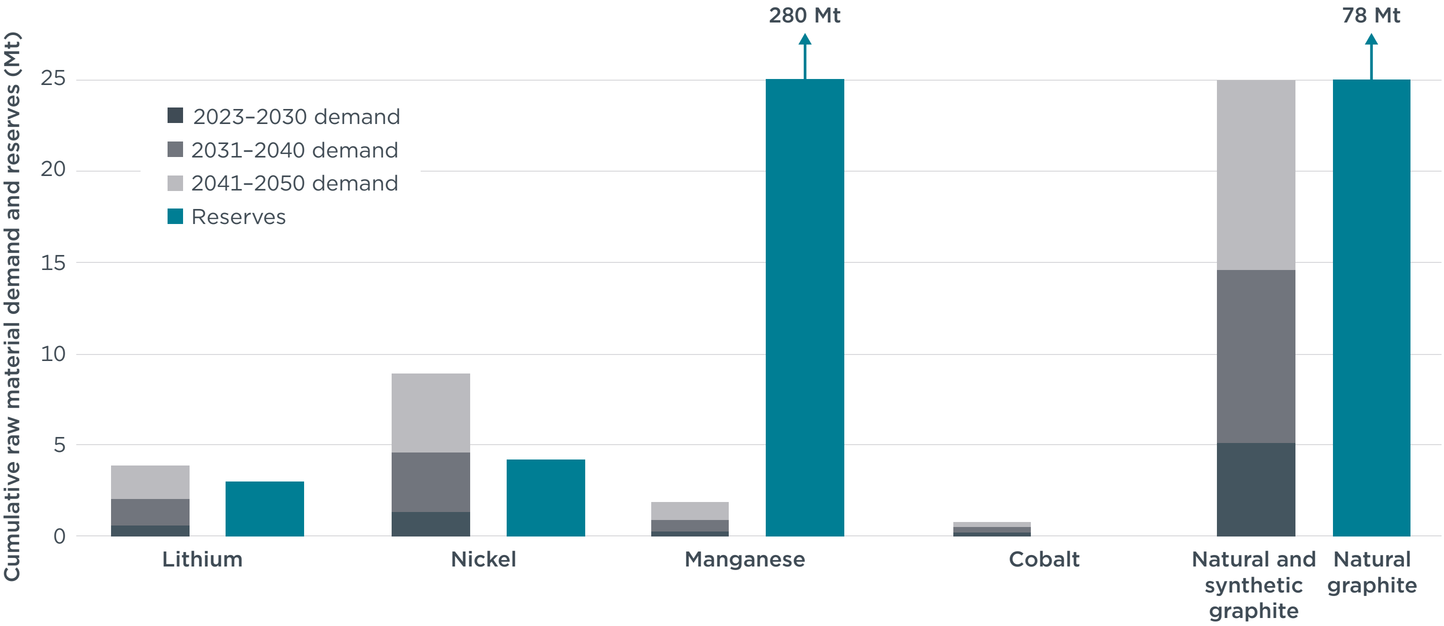

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Figure A12

Annual raw material demand for lithium, nickel, cobalt, graphite, and manganese in the European Union under the Baseline and alternative battery technology mix scenarios

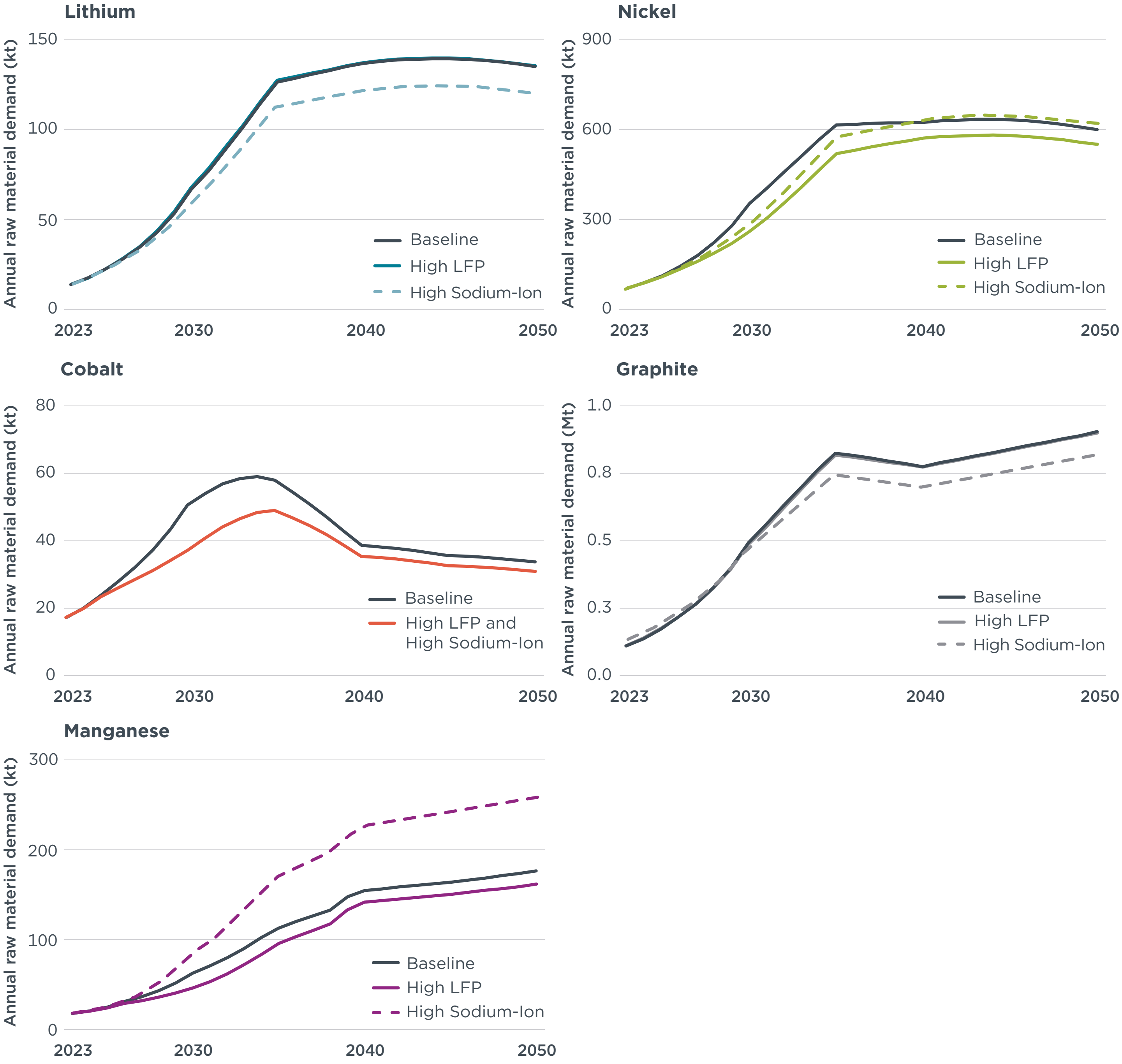

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Figure A13

Annual raw material demand for manganese in the European Union under the Baseline and demand reduction scenarios

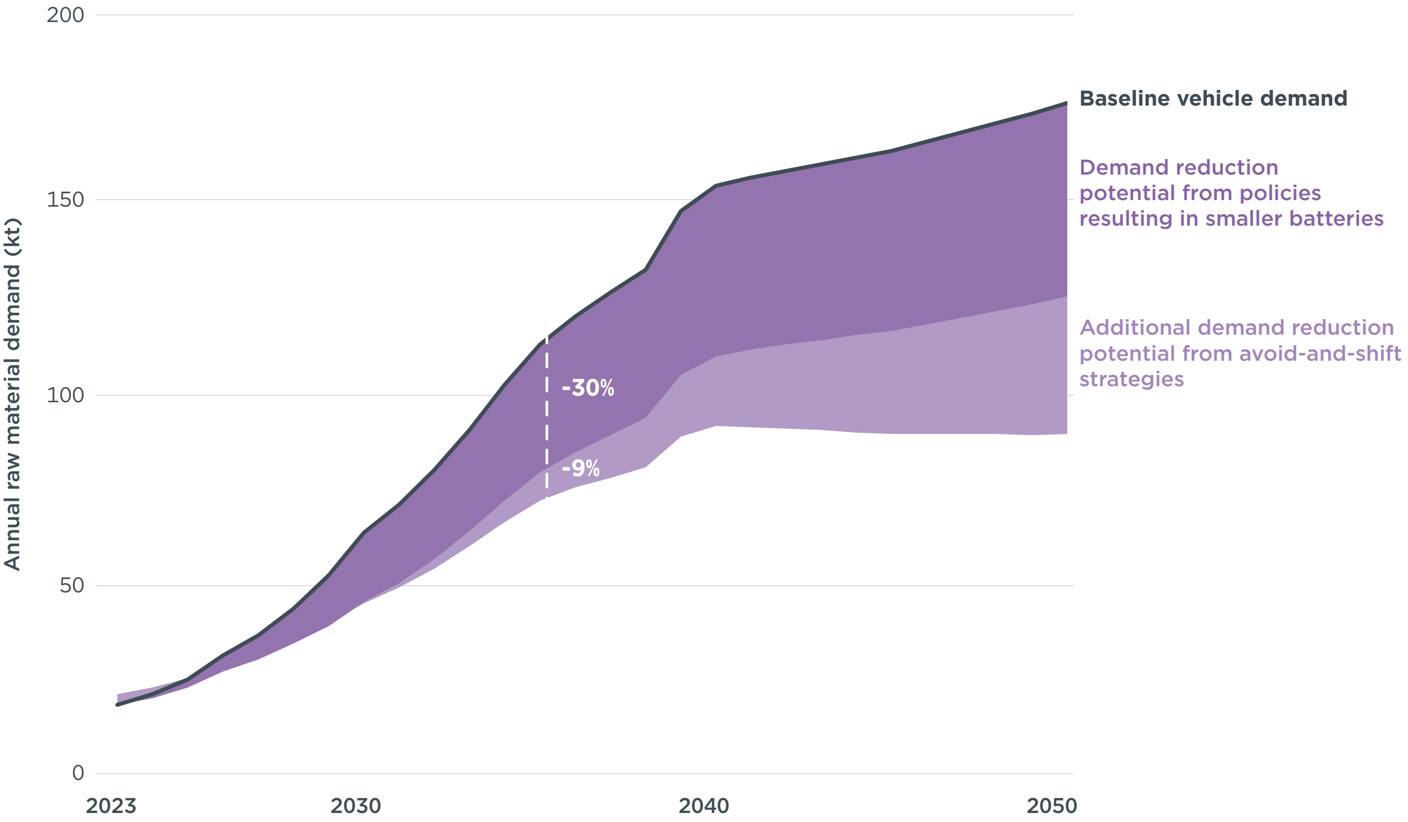

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Figure A14

Cumulative raw material demand and reserves in the European Union

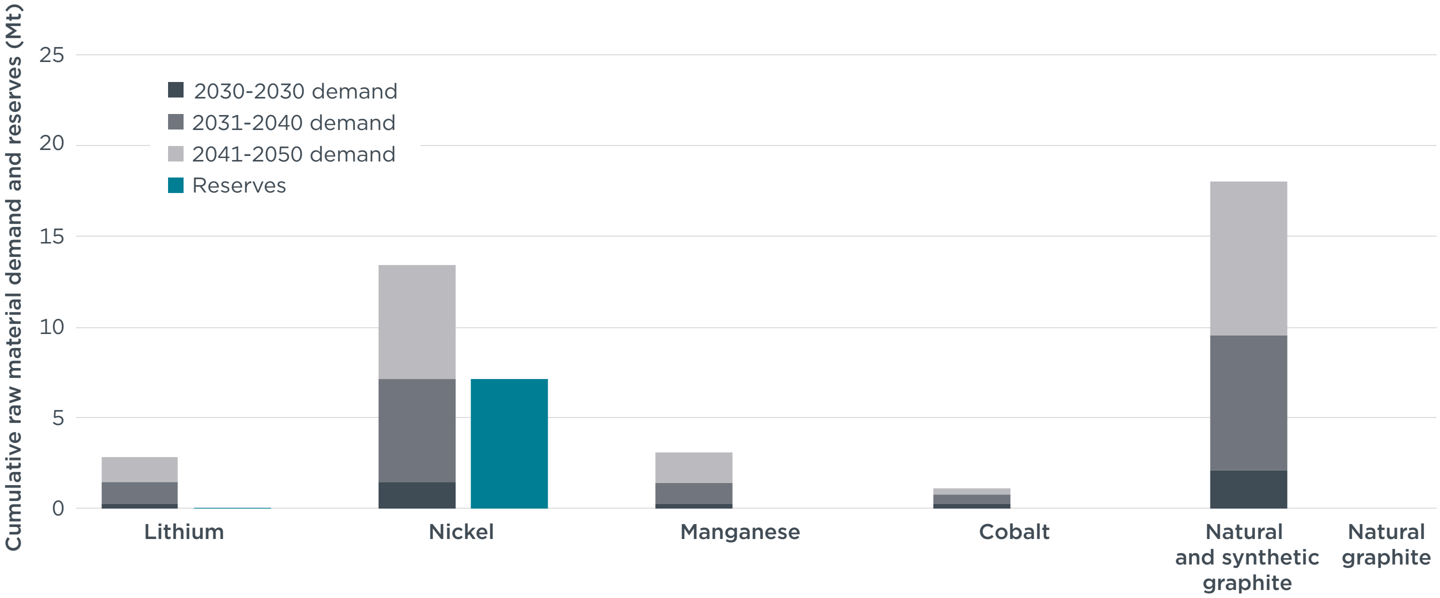

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Figure A15

Annual raw material demand for lithium, nickel, cobalt, graphite, and manganese in India under the Baseline and alternative battery technology mix scenarios

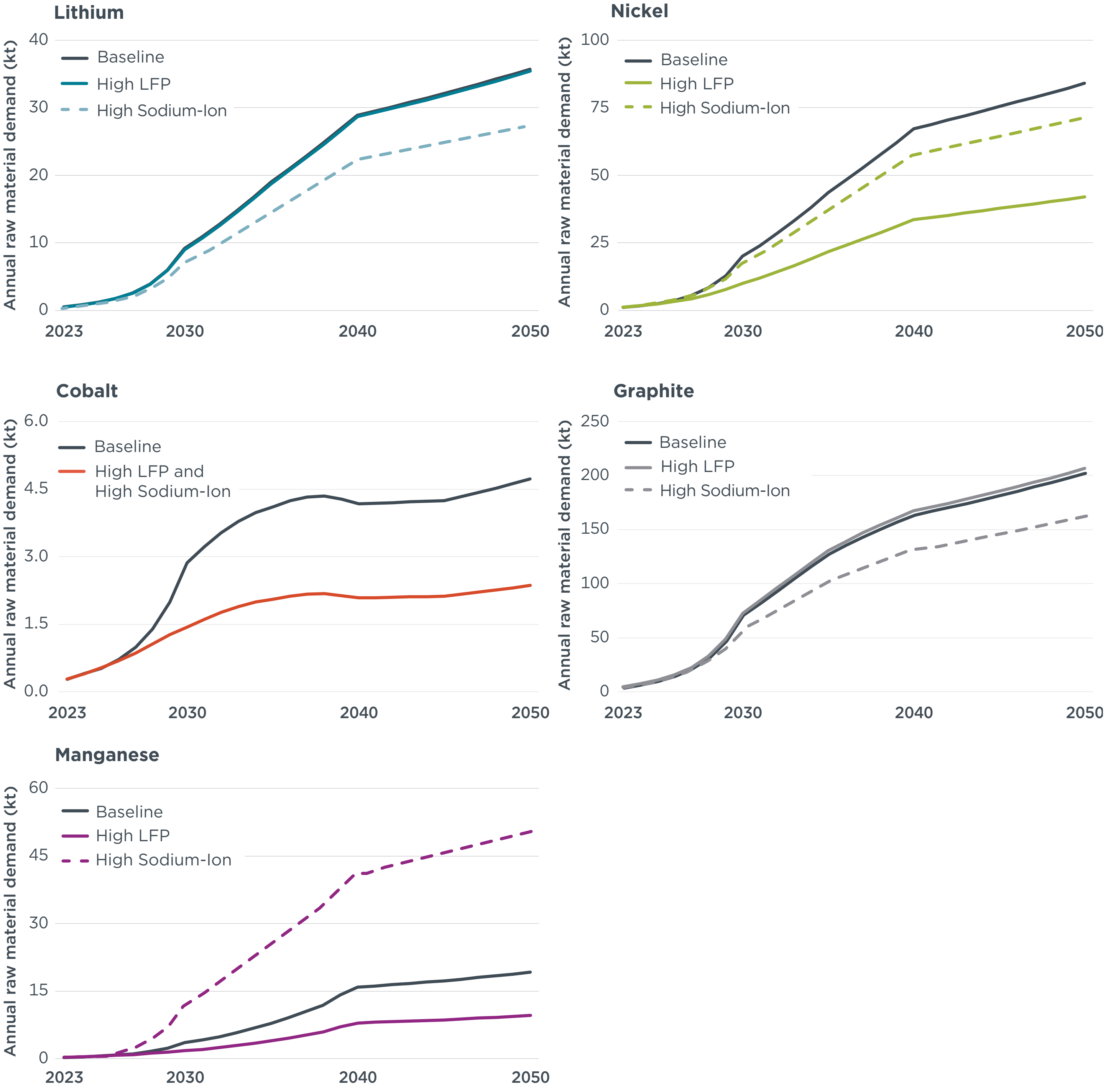

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Figure A16

Annual raw material demand for manganese in India under the Baseline and demand reduction scenarios

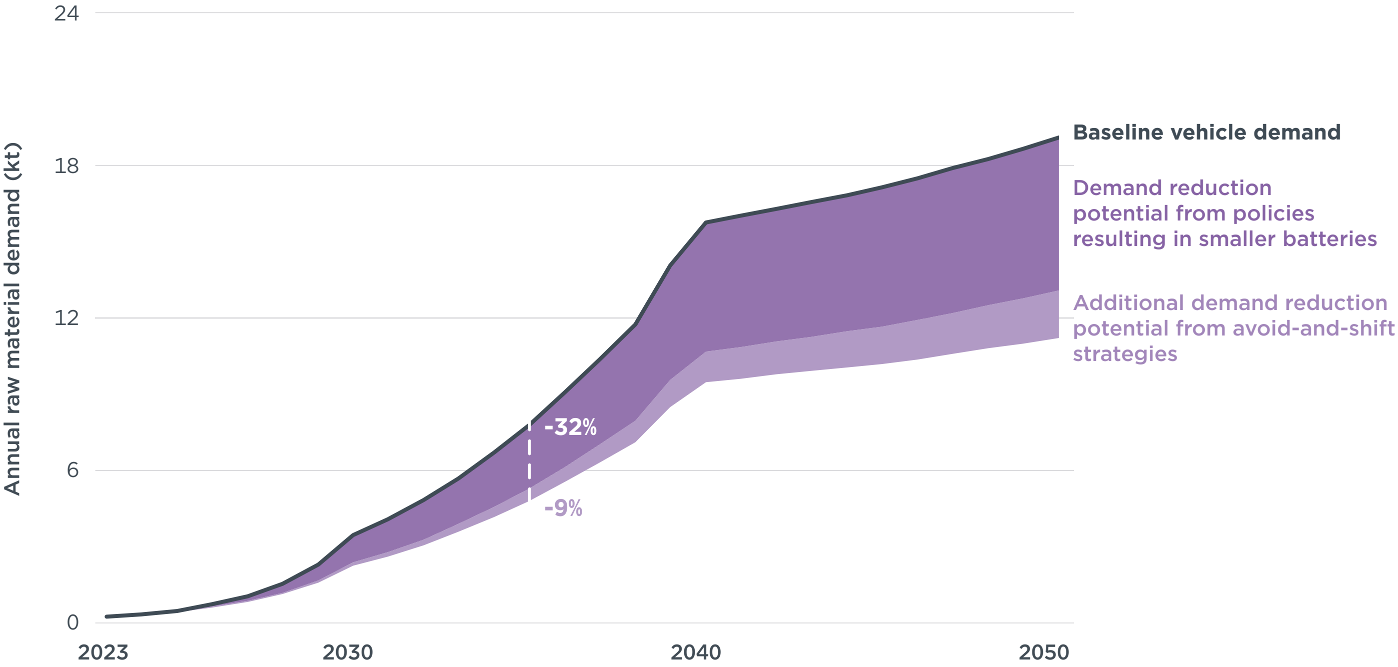

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Figure A17

Cumulative raw material demand and reserves in India

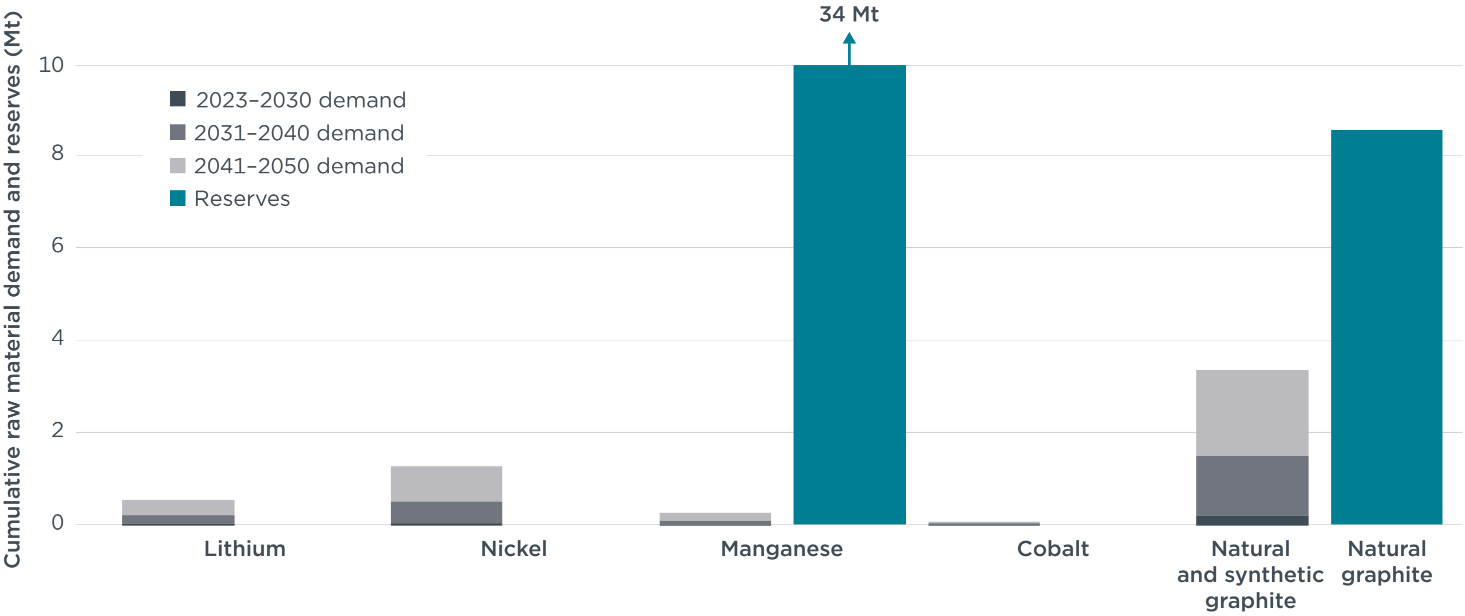

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Figure A18

Annual raw material demand for lithium, nickel, cobalt, graphite, and manganese in Indonesia under the Baseline, High LFP Share, High Sodium-Ion Battery Share, and NMC-leaning battery technology mix scenarios.

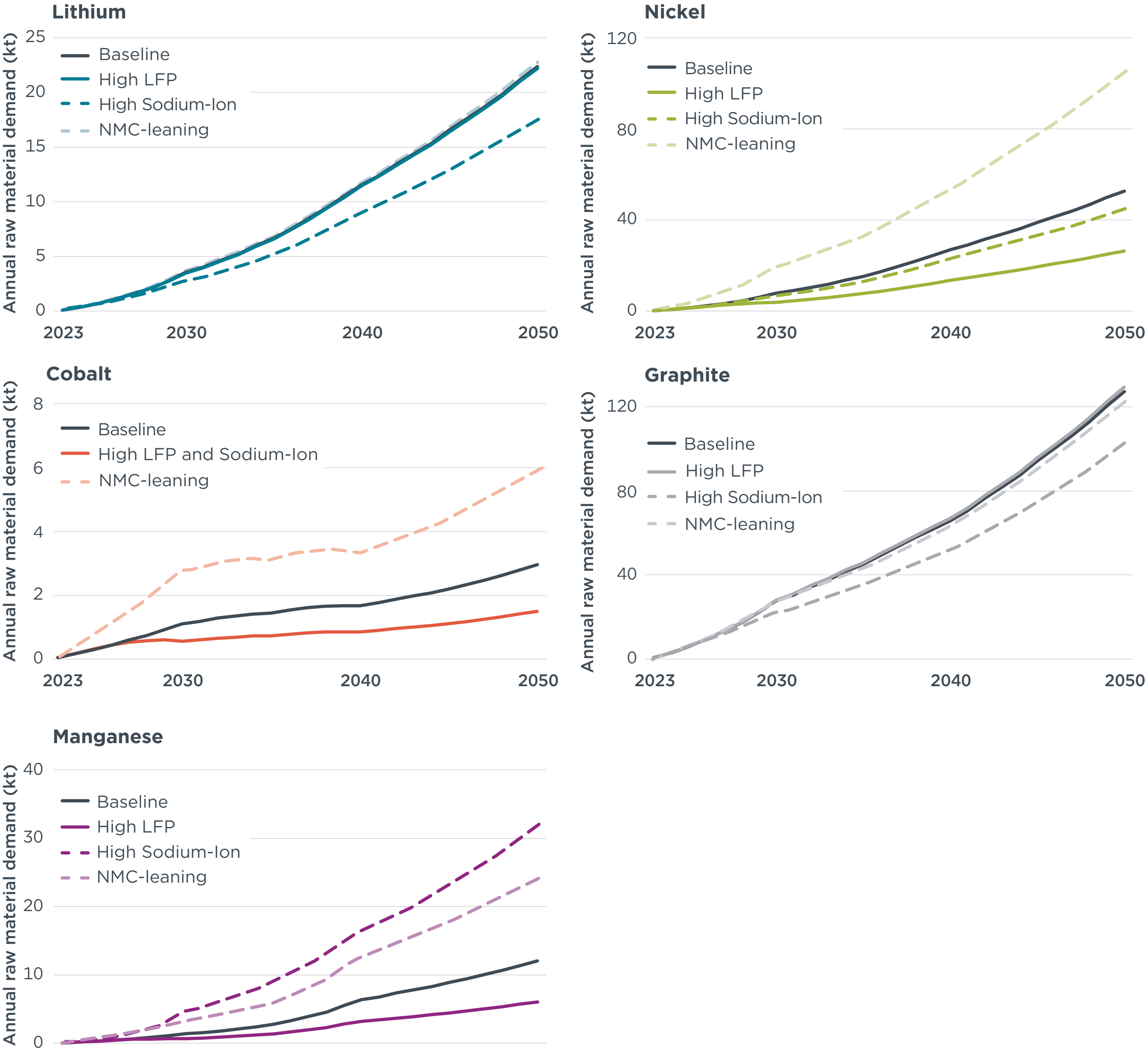

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Figure A19

Annual raw material demand for manganese in Indonesia under the Baseline and demand reduction scenarios

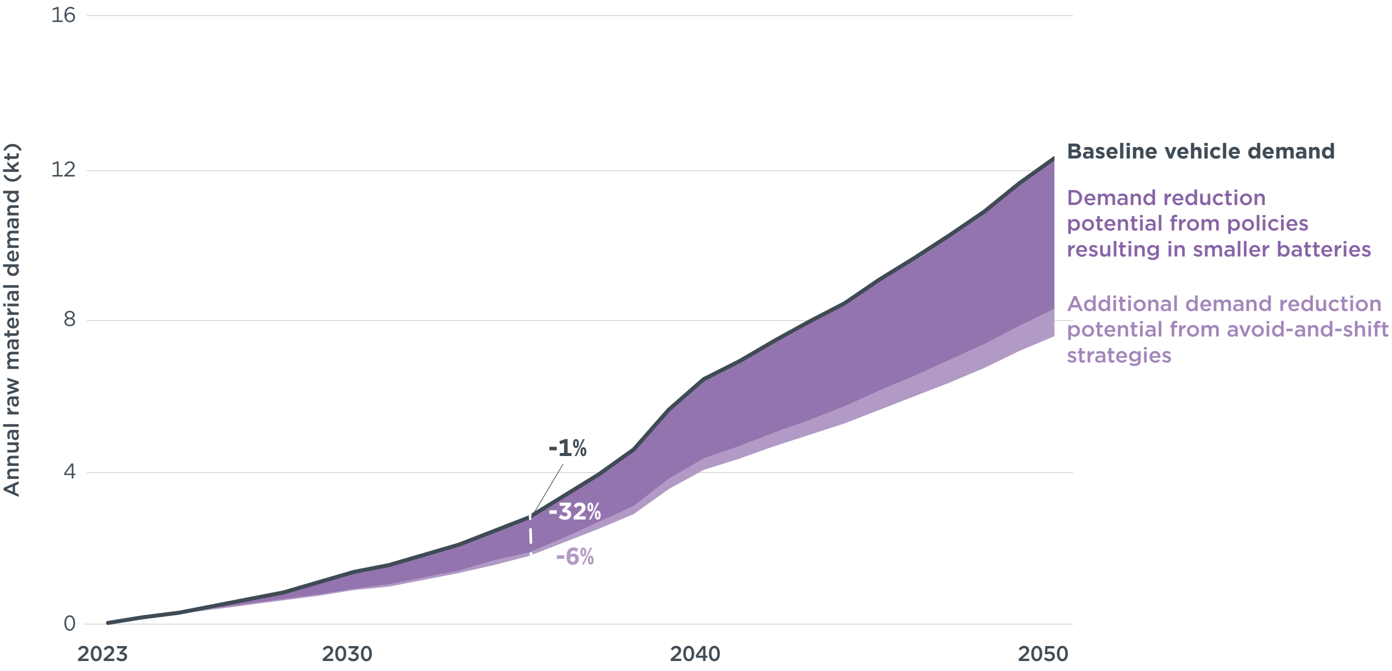

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Figure A20

Cumulative raw material demand and reserves in Indonesia

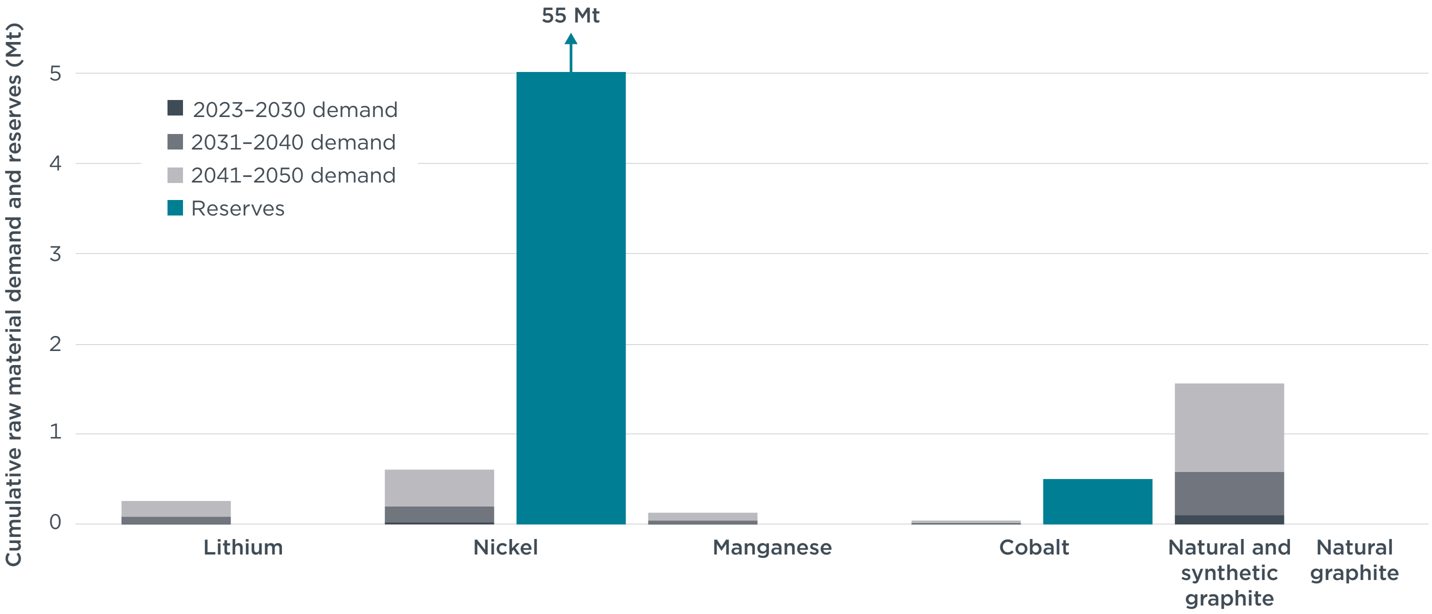

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Figure A21

Annual raw material demand for lithium, nickel, cobalt, graphite, and manganese in the United States under the Baseline and alternative battery technology mix scenarios

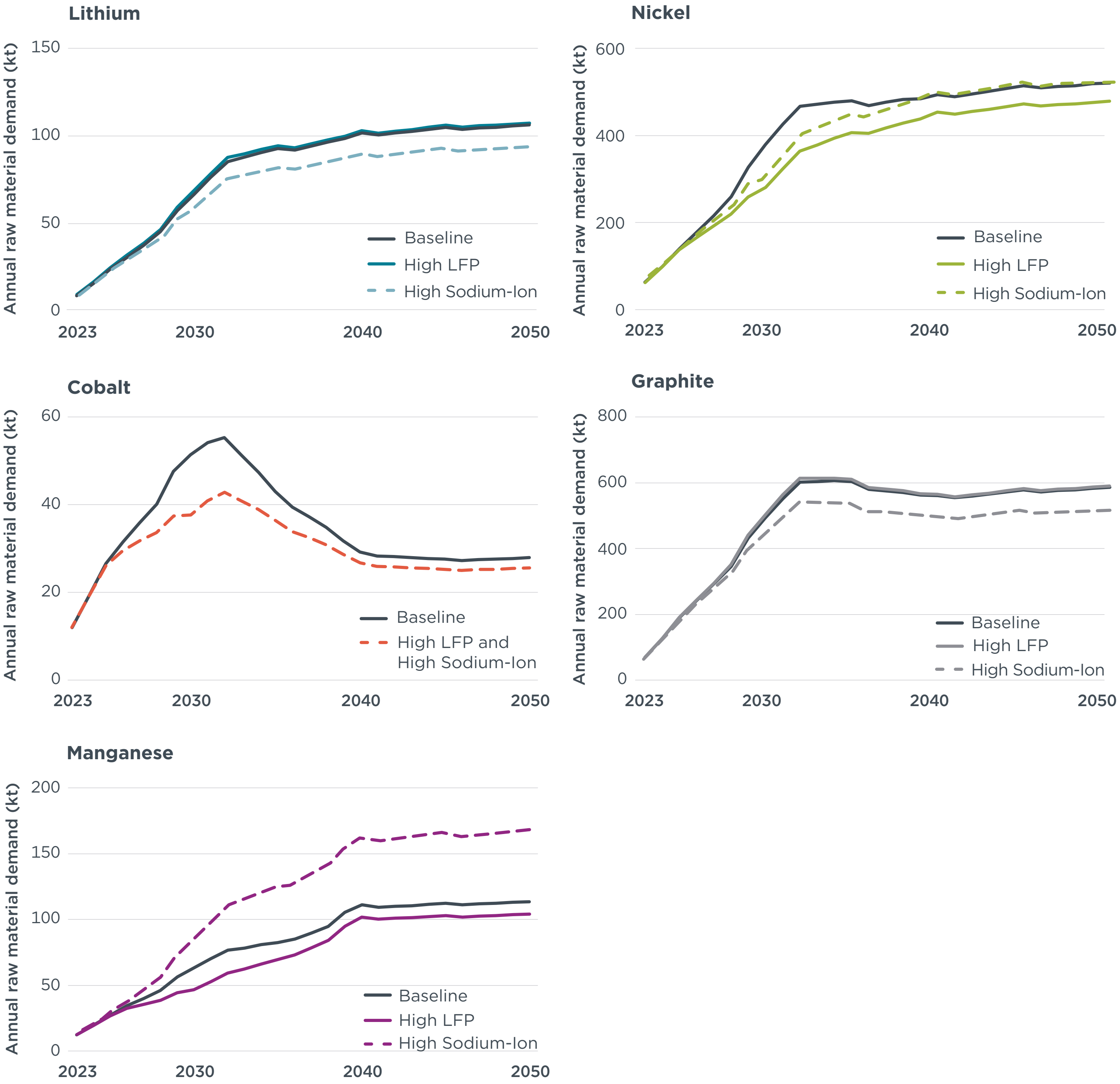

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Figure A22

Annual raw material demand for manganese in the United States under the Baseline and demand reduction scenarios

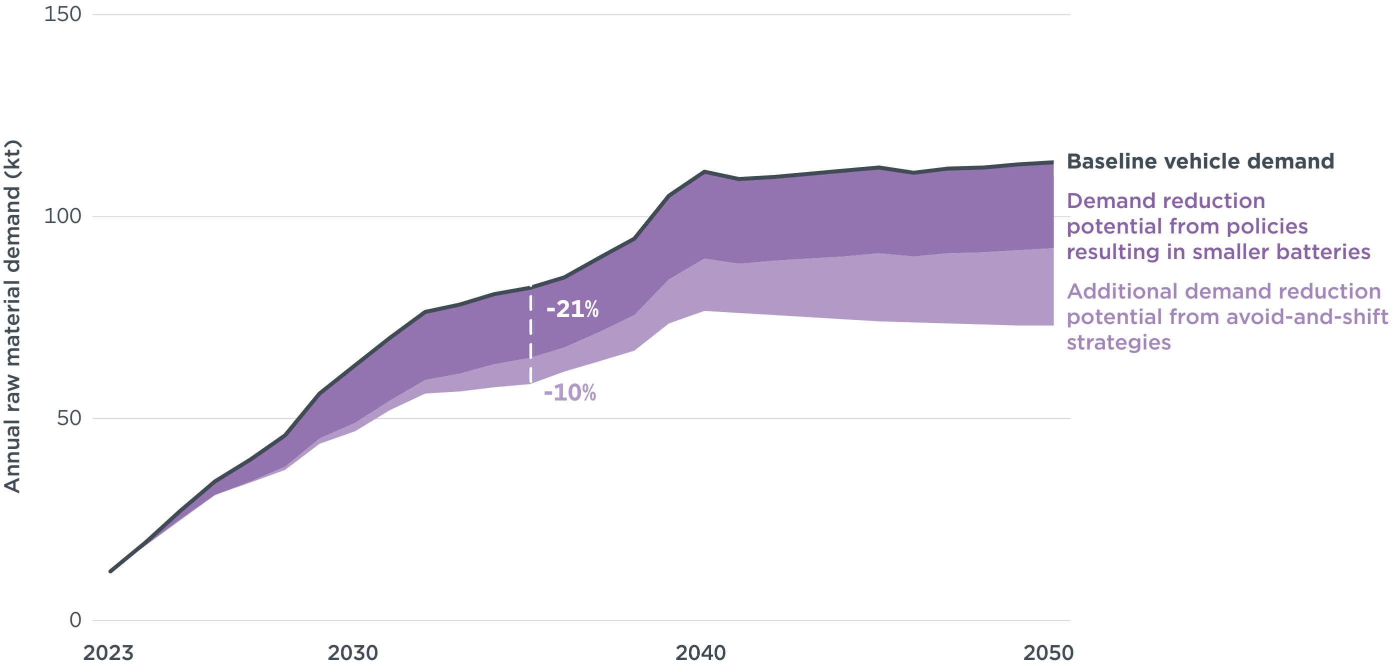

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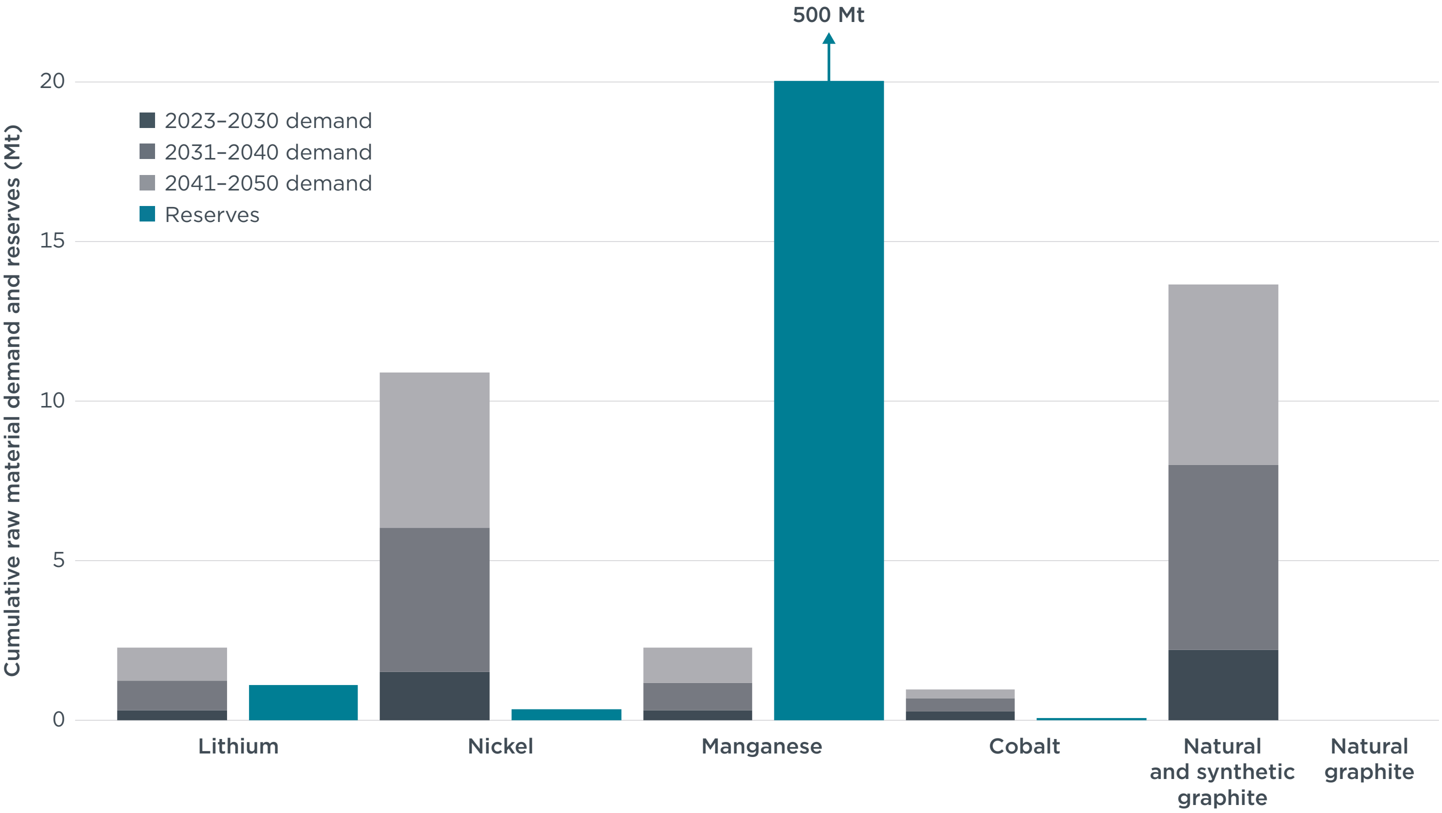
Figure A23

Cumulative raw material demand and reserves in the United States



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www.theicct.org

communications@theicct.org

@theicct.org

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