The Battery Mineral Loop

The path from extraction to circularity

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About RMI

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Executive Summary

Battery minerals are *not* the new oil. Even as battery demand surges, the combined forces of efficiency, innovation, and circularity will drive peak demand for mined minerals within a decade. They could even allow us to avoid mineral extraction altogether by 2050. These advancements enable us to transition from a linear extraction model to a circular loop, with compounding benefits for our climate, security, health, and wealth.

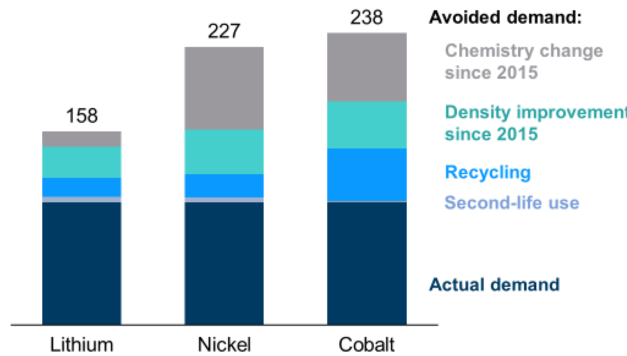
- **There are six solutions to mitigate the need for mineral mining.** These include deploying new battery chemistries, making batteries more energy-dense, recycling their mineral content, extending their lifetime, improving vehicle efficiency, and improving mobility efficiency.
- **Change is already underway.** Without the past decade of chemistry mix, energy density, and recycling improvements, lithium, nickel, and cobalt demand would be 60%–140% higher than they are today. The majority of global lithium-ion batteries already get recycled today.
- **Peak mineral demand is only a decade away.** Continuing the current trend means we will see peak virgin battery mineral demand in the mid 2030s. As chemistry mix, energy density, and recycling continue to improve, the net demand — total demand minus recycled supply — will peak for lithium, nickel, and cobalt.
- **Net-zero mineral demand before 2050 is within reach.** Accelerating the trend— using all six solutions above — means we can reach (near) zero mineral mining demand before 2050, when virtually all battery demand can be met through recycling.
- **So mineral mining will be a one-off effort.** End-of-life batteries will become the new mineral ore, limiting the need for battery mineral mining in the long term. After using a battery for 10–15 years, its mineral content can be collected and recycled at 90-94%+ efficiency. So improving overall battery and transport system efficiency by 6-10% per decade is enough to offset recycling losses.
- **Circularity will kickstart a "perpetual motion machine."** Such a closed-loop supply chain means we can continue to derive value from battery minerals for centuries. Over the next 20 years, we will gather minerals not just to power the energy system of 2050, but also through to 2100 and beyond.
- **We won't have to move mountains.** Accelerated progress means we only need to mine a cumulative 125 million tons of battery minerals. This quantity alone can get us to circular battery self-sufficiency. That is 17 times smaller than the amount of oil we extract and process for road transport *every year*. And, at today's commodity prices, about 20 times cheaper as well.
- **We have enough minerals.** Our known reserves of lithium, cobalt and nickel are twice the level of total virgin demand we may require. And announced mining projects are already sufficient to extract almost all the minerals we need.
- **Countries can move from oil dependence to circular independence.** Most economies would grind to a halt if oil imports were to stop. Electric vehicles powered by renewables face no such short-term risk, especially when paired with battery recycling and (re)manufacturing.
- **China leads the battery circularity race to the top.** China's largest battery manufacturer, CATL, expects battery recycling to lead to mineral independence in China by 2042. The West is trying to catch up, while the Global South can benefit from the batteries in their used vehicle imports.
- **Systemic solutions will broaden the benefits.** The more holistically we approach demand through efficient batteries, vehicles, and mobility, the broader the benefits for the climate, human rights, security, health, and wealth.
- **To accelerate action, we need all stakeholders to lean in.** From governments to corporate innovators, all have a role to play in capturing the circular opportunity.

Exhibit 1: The battery mineral loop in six charts

There are six solutions to curbing battery mineral demand…

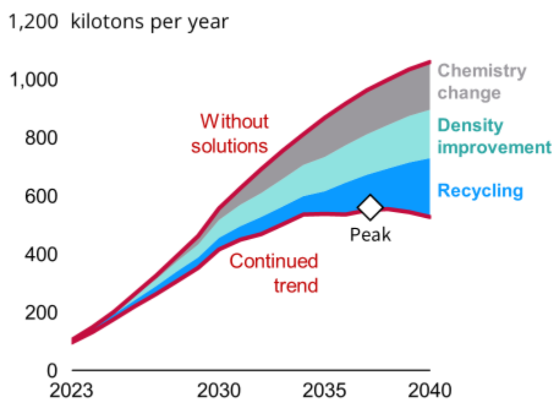
…of which three have already made a major impact.

Virgin mineral demand for batteries in 2023, actual demand = 100



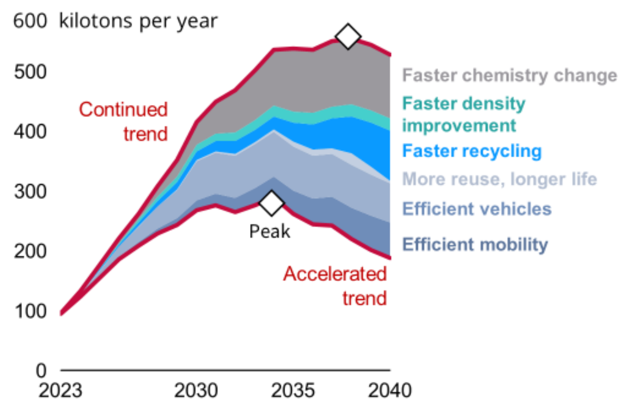
Continuing this trend leads to peak battery mineral demand in the 2030s…

Net lithium demand, fast uptake



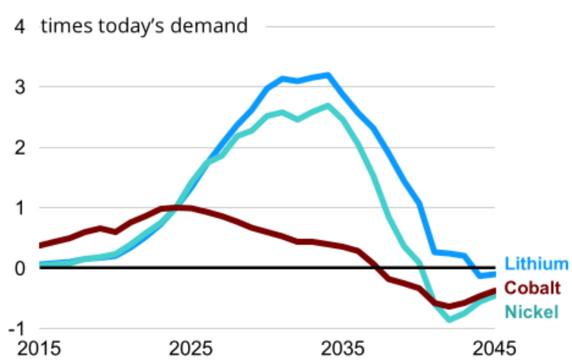
…while accelerating the trend along all six solutions can avoid most long-term demand.

Net lithium demand, fast uptake



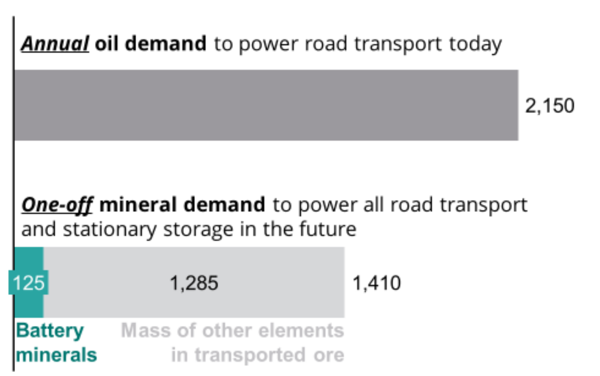
Net-zero battery mineral demand is achievable before 2050…

Net battery mineral demand, faster uptake, accelerated trend



…powering our lives with a tiny and temporary fraction of the extraction that fossil fuels require.

Virgin extraction, million tons, faster uptake, accelerated trend



Note: All tons in this report are metric tons.

Source: RMI analysis; BloombergNEF (2024), IEA *Global EV Outlook and Critical Minerals Outlook* (2024), USGS National Minerals Information Center

1. The six solutions to the battery mineral challenge

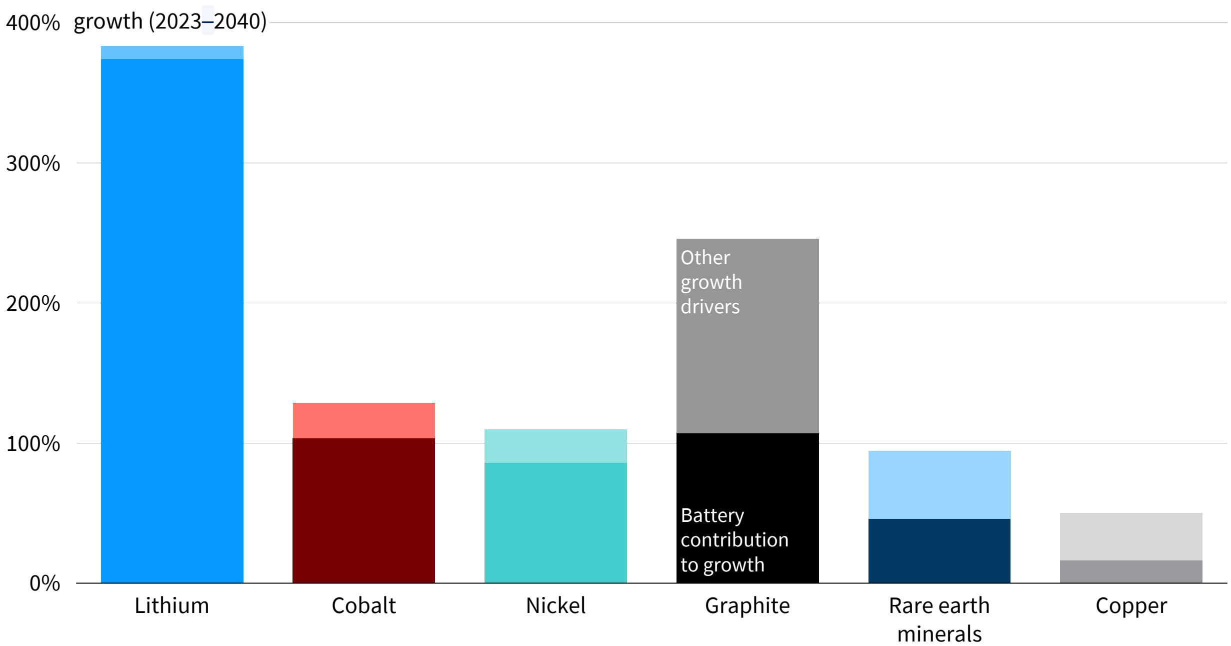
The energy transition is a materials transition. As the transition accelerates, some materials will go into decline, while others need to scale up rapidly to meet new demands.

As described in the latest IEA minerals report,[1] the materials that are currently under most scaling pressure are lithium, cobalt, nickel, graphite, rare earth elements, and copper.

Batteries are a key driver of this growth. Batteries are made up of different combinations of materials purified from specific minerals,[i] and as battery sales are set to grow, so will mineral demand. According to the IEA, batteries will drive 97% of the increase in lithium demand, 78% of nickel, and 80% of cobalt, while also raising demand for copper, graphite, and rare earth elements.

In this report, we focus on mineral demand from the battery sector, highlighting the three minerals — lithium, nickel, and cobalt — where batteries are the biggest contributor to growth. Many of the takeaways will hold true for graphite, copper, and other key minerals as well. The following sections discuss six solutions to manage mineral demand growth, then lay out two possible futures.

Exhibit 2: IEA Outlook mineral demand growth from 2023 to 2040



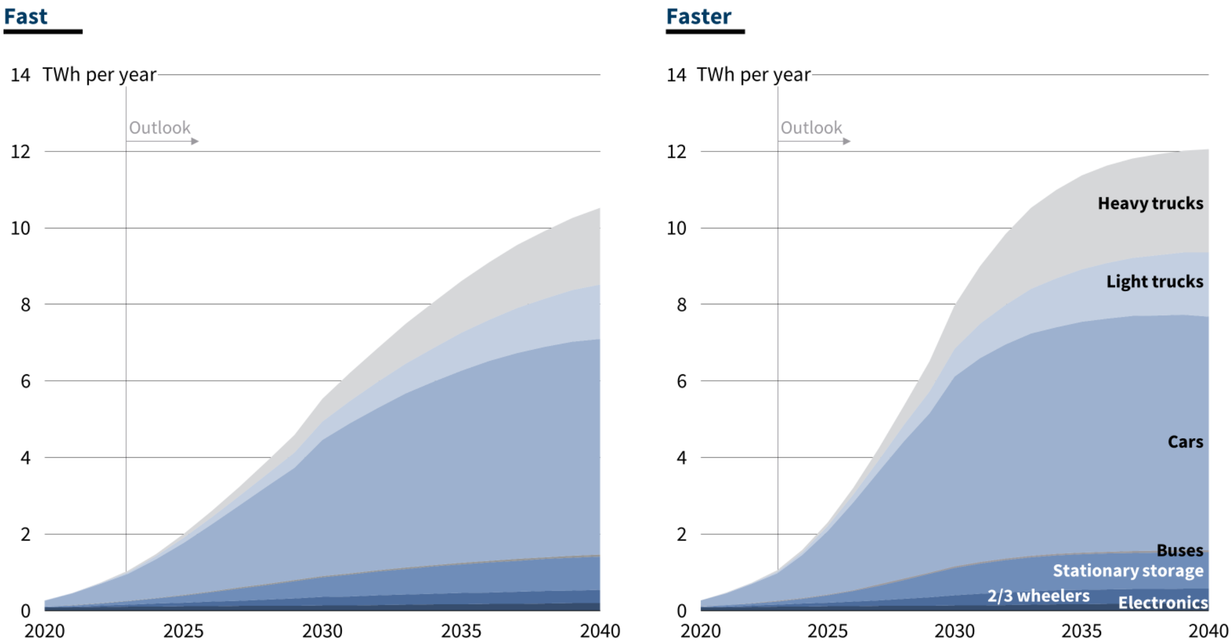
Source: IEA Global Critical Minerals Outlook (2024)

The battery mineral challenge

Battery demand is rising exponentially — growing at a breakneck pace of 33% per year for the past three decades. As described in detail in our report *X-Change: Batteries*,[2] growth looks set to continue at either a Fast or Faster pace. Total battery sales exceeded 1 TWh in 2023, and will grow to 5.5–8 TWh by 2030 and 12 TWh by 2050.[3] This includes approximately 1 TWh for stationary grid storage, a fraction of that for consumer electronics, and the rest for mobility.

[i] This report uses "minerals" as shorthand for mined materials (usually chemical compounds of desired elements), as well as the valued products that are extracted from them after mining.

Exhibit 3: Annual battery demand, Fast and Faster scenario



Source: RMI *X-Change Batteries;* RMI analysis

As battery sales rapidly rise, the demand for the minerals that batteries are made of — currently lithium, cobalt, nickel, and more — will grow.

Many of these minerals come from previously niche mining sectors. For example, before the rise of lithium-ion batteries in the 1990s and 2000s, lithium was a niche element with marginal demand in ceramics, glass, and some aluminum production. As demand for lithium-ion batteries grew, the lithium supply sector had to overhaul itself to meet the rapid pace of growth, growing at over 11% per year over the past 30 years.[4]

This has not gone without stresses on the supply chain. For example, it was only late in 2023 that lithium, nickel, and cobalt prices retreated from an 18-month spike caused by extreme market tightness.[5]

This situation has sparked widespread concern regarding the sustainability of ramping up mineral mining to meet demand, as well as the long-term availability of these essential minerals. This scaling challenge is increasingly recognized as a primary hurdle to the growth of the battery sector, and consequently, to the rise of electric vehicles.

Moreover, increased mining could bring increased impacts on vulnerable communities — including the use of forced labor, dangerous working conditions, water depletion, soil contamination, biodiversity loss, and disruption to local economies.[6] For example, mining is the top sector driving global environmental conflicts with Indigenous peoples.[7] Even if mineral mining can be increased, there are many reasons to pursue other solutions.

Thankfully, scaling up mineral mining is far from the only solution to the battery mineral challenge.

Six solutions

As outlined by Amory Lovins in 2021, there are six key solutions to manage rapid mineral demand growth[8] — shown here in rough decreasing order of impact on demand so far:

A. **Changing chemistries**: Deploy different battery chemistries that require fewer critical minerals.

B. **Higher energy density batteries**: Store more energy per kilogram through better battery engineering.

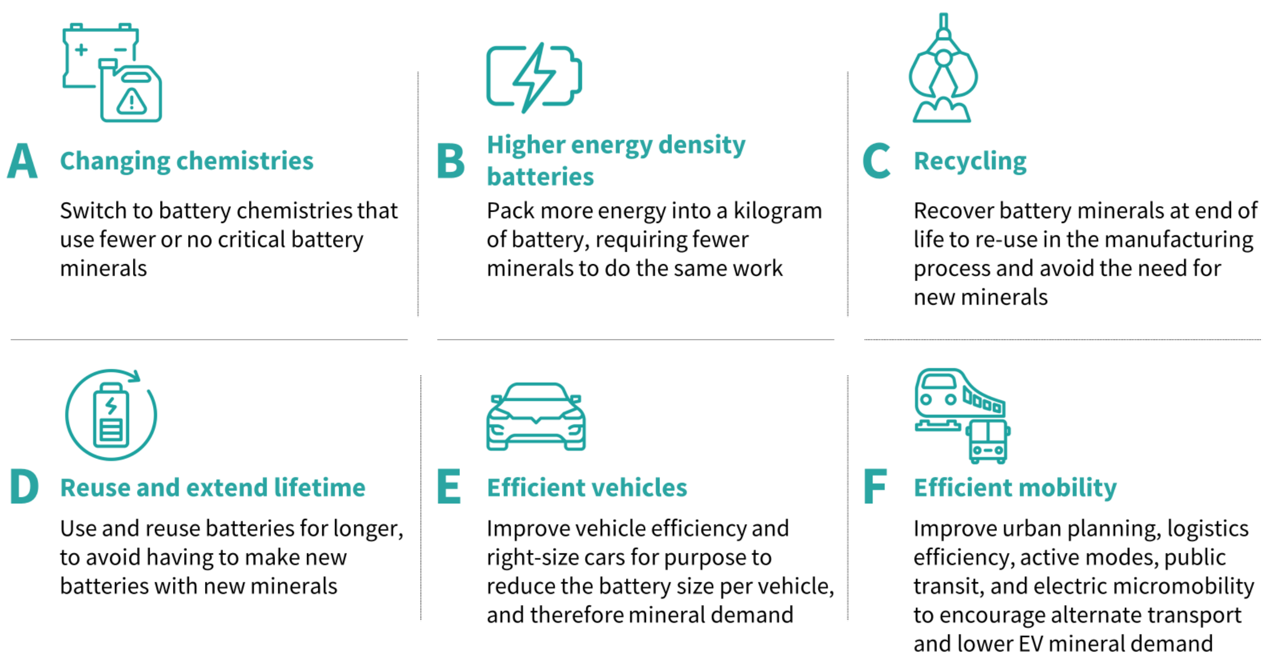
C. **Recycling**: Recycle batteries at the end of their life to reuse their minerals for new battery production.

D. **Reuse and extend lifetime**: Use and reuse batteries longer, to avoid frequent replacements and provide a greater flow of service from a smaller stock of batteries and their minerals.

E. **Efficient vehicles**: Make cars more efficient — lighter-weight, sleeker, with better tires and accessories — and right-size them for purpose to allow for smaller batteries for the same vehicle range.

F. **Efficient mobility**: Reduce the demand for motorized transportation and induce mode-shifts to public transit, electric micromobility, cycling, and walking through better urban planning, smarter transportation infrastructure investments, and logistics efficiency.

Exhibit 4: The six solutions to the battery mineral challenge



Source: Amory Lovins, "Six Solutions to Battery Mineral Challenges" (2022)

Solutions are already underway

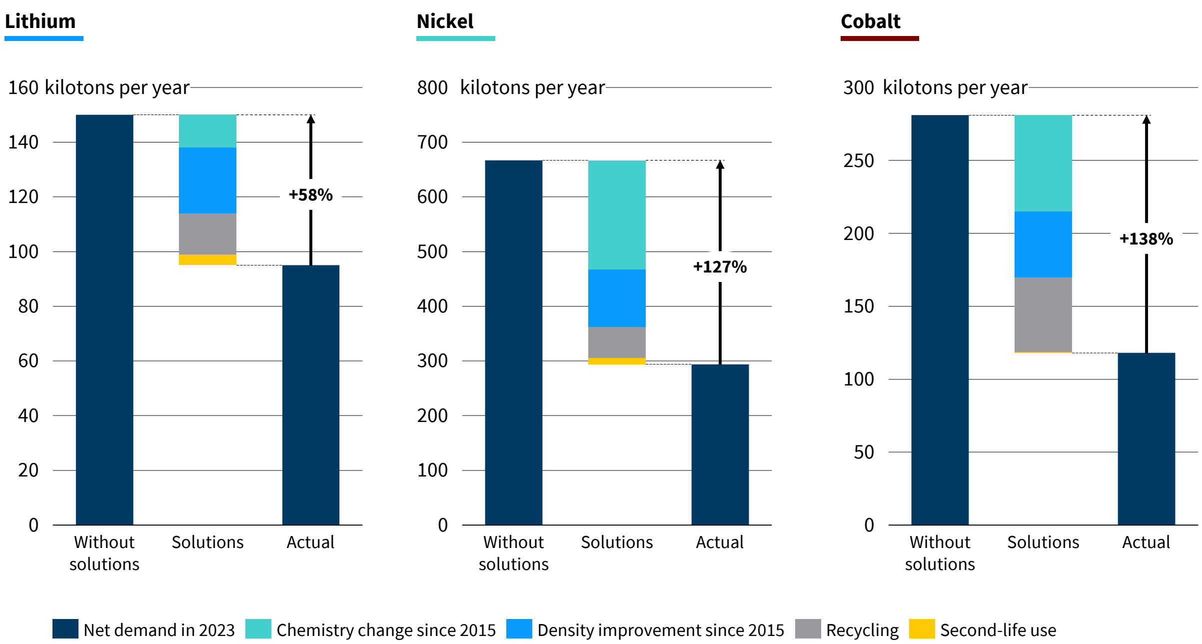
Three of these six solutions have *already* significantly reduced battery mineral demand. If we had continued to make batteries just as we did in 2015 (and didn't reuse or recycle any of them), nickel and cobalt demand in 2023 would have been more than twice as high, and lithium demand would be about 58% higher.

Chemistry change was the primary driver of curbing nickel and cobalt demand, driven by the growth of lithium iron phosphate (LFP) batteries that need no nickel and cobalt.

Average density for each chemistry has also improved by approximately 25% since 2015,[9] lowering the mineral demand per battery. And some of that demand is now being met by recycling, which was already in place for more than half of lithium-ion batteries globally in 2019.[10]

Driven by scarcity concerns, we have already come a long way to mitigate mining demand with these solutions. As Lovins has illustrated,[11] actual or perceived resource scarcity can inspire solutions that may help to displace a resource altogether.

Exhibit 5: The impact of chemistry changes, energy density, and recycling on net mineral demand in 2023



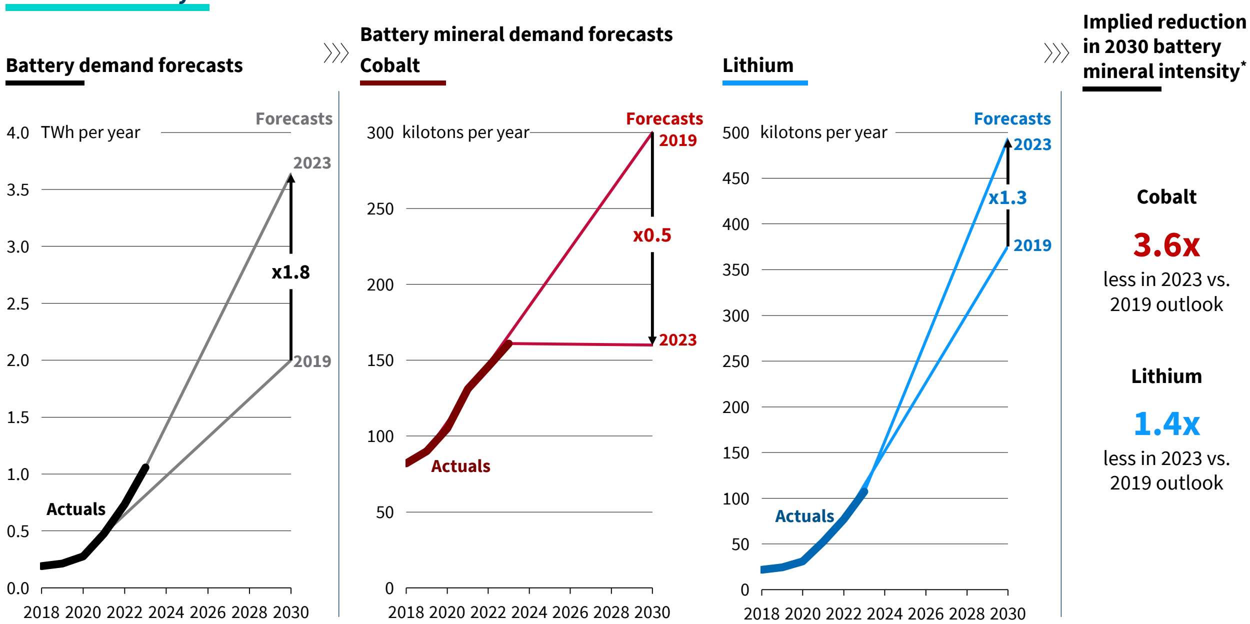
Source: RMI analysis. Recycling includes recycling of production scrap, which is generally economic already.

Expert outlooks keep underestimating the pace of change

Experts keep underestimating the pace at which the battery sector manages to innovate minerals out of batteries. Outlooks keep correcting battery mineral demand downward, even as battery demand forecasts are corrected upward.

For example, the BloombergNEF (BNEF) outlook for battery demand in 2030 was raised by a factor of 1.8 in just four years (from 2019 to 2023).[12] But as batteries shifted chemistries and improved their densities, the associated lithium demand only rose by a factor of 1.3, and projected cobalt demand fell by half. Thus, over that four-year period, the projected 2030 mineral demand per battery fell by more than 3.6x for cobalt and 1.4x for lithium.

Exhibit 6: Battery demand forecasts versus mineral demand forecasts



** Derived by dividing the battery demand increase by the change in mineral demand between the 2019 and 2023 outlook.*

Source: BNEF Long-Term Electric Vehicle Outlook (2019—2023), RMI analysis

2. Continuing the current trend: peak battery minerals in a decade

As battery sales grow, the demand for minerals will rise with it. But growing battery demand tenfold will not necessarily raise battery mineral demand by a factor of 10. Three solutions to the battery mineral challenge — chemistry changes, density improvements, and recycling — have already been curbing mineral demand.

This section explores what a continuation of these three trends will mean for battery mineral demand. We find that under continued trends, virgin mineral demand will peak around the mid-2030s.

The drivers of continued change

In this sub-section we lay out what a continuation of the global trend in chemistry changes, density improvements, and recycling improvement means.

The chemistry mix continues to evolve

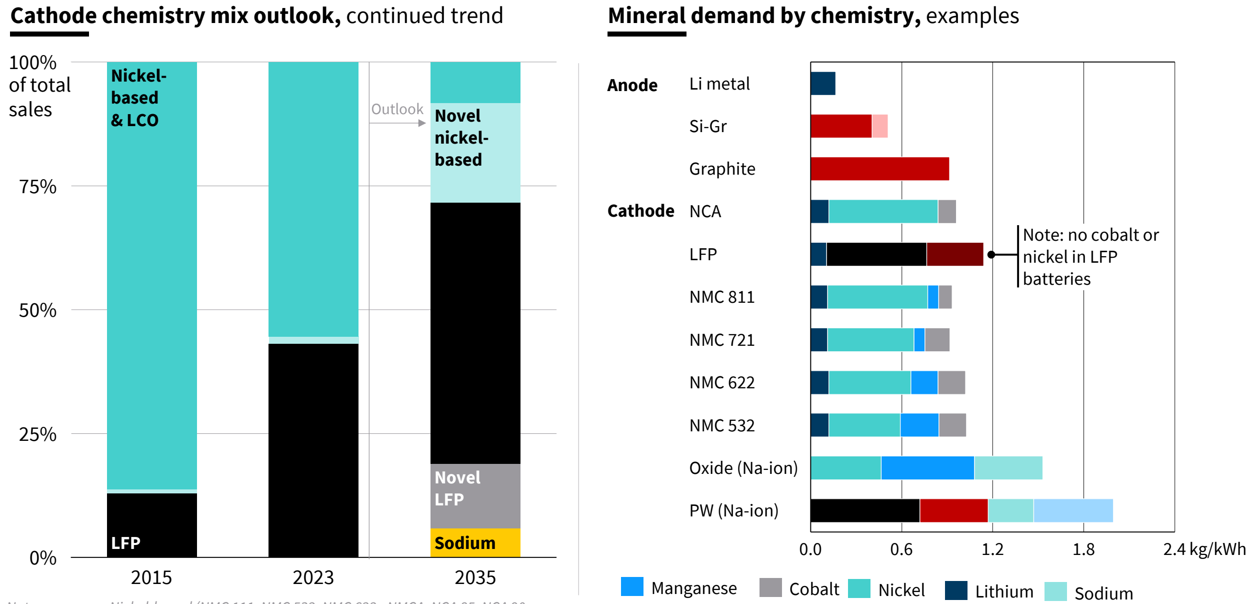
As battery innovation continues and sales scale to new applications and sectors, the mix of battery chemistries used in new technology will change. Different battery chemistries use varying amounts of minerals, so a change in chemistry mix changes the demand for each mineral.

For example, moving from nickel manganese cobalt (NMC) 532 to NMC 811 reduces the cobalt demand of a battery by more than half, though at the expense of higher nickel demand. Moving to LFP can get rid of all nickel and cobalt demand, both replaced by iron and phosphorus.

New chemistries are set to grow in the coming decade, as forecasted in BNEF's chemistry mix outlook — leading to a continued shift in battery mineral demand. Different chemistries are also diverging for distinct costs and use cases, much as lower-cost electric cars favor cheaper LFP.

In just the past year, LFP technology and cost improvements *doubled* the projected LFP share of commercial vehicle batteries (from ~40% to ~80%), with significant increases for passenger vehicles as well.[13] That change led to a drop in projected nickel demand by 25%–35%.[14]

Exhibit 7: Battery mineral demand by chemistry and chemistry mix



Note on groups: Nickel-based (NMC 111, NMC 532, NMC 622,, NMCA, NCA 85, NCA 90, LMO, LNMO, LCO), Novel nickel-based (NMC 955, NMC 811, NMC 721, NMC 96Ni, LMR-NMC, NCA 92, NCA 95, eLNO), LFP (LFP), Novel LFP (LMFP), Sodium-based (Na-ion)

Source: BNEF Long-Term Electric Vehicle Outlook (2024), IEA Global EV Outlook (2024), RMI analysis. Includes all sectors of battery demand.

Innovation keeps increasing energy density

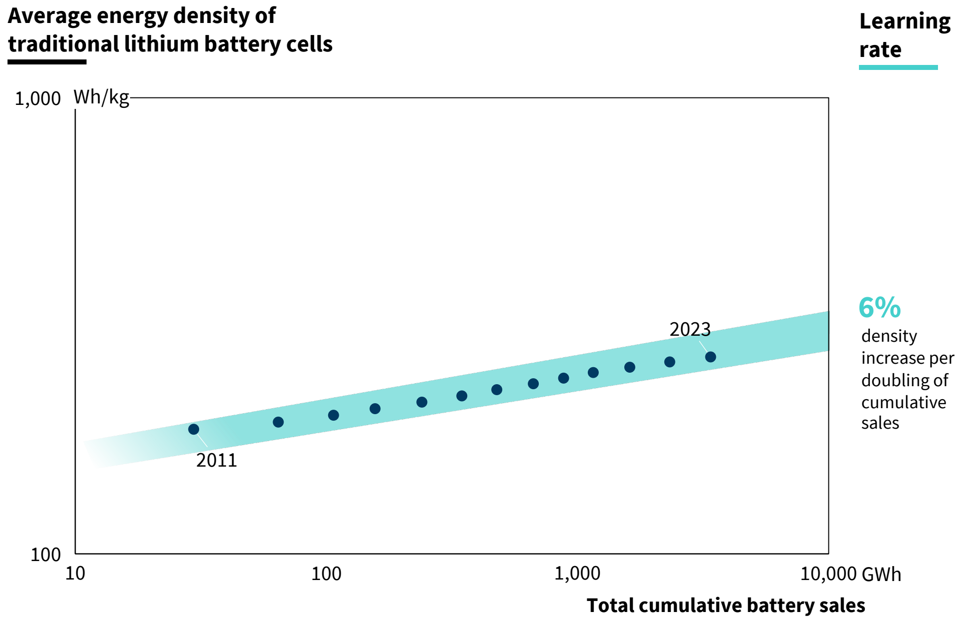
As battery sales increased in past decades, the energy density of batteries rose, driven by growing R&D budgets and economies of scale. This report focuses on battery *cell* densities to understand the effect on mineral demand — though there are other improvements in pack-level components as well.

On average, for every doubling of cumulative battery demand, the average energy density of lithium-ion battery cells (kWh/kg) rose by about 6%. As battery demand grows, we can expect energy density to rise with it — storing more electricity in fewer kilograms.

Part of the historic density improvement came from chemistry changes — shifting from less to more energy-dense battery chemistries. We estimate that this accounts for about 2% of the 6% improvement per doubling of cumulative demand. Hence the net learning rate of energy density improvements (for a given chemistry) is about 4%, or two-thirds of the total learning rate.

As battery deployment doubles at least another 4 to 5 times before 2050, density can be expected to rise by over 25%.

Exhibit 8: Average energy density learning rate for lithium-ion battery cells



Source: BNEF *Lithium-Ion Batteries: State of the Industry* (2023), RMI analysis

Recycling continues to grow

Battery recycling is already well underway.

According to the research and consulting firm Circular Energy Storage, 59% of all lithium-ion batteries were recycled globally in 2019,[15] and their more recent assessments suggest it could be as high as 90% today.[16] BNEF now estimates global collection rates of 60% or above for most sectors. In any case, the collection rate is much higher than the often cited but clearly wrong figure of only 5%. We provide more detail in Appendix C and F.

Of the batteries that are collected and recycled, 80% to 95% of minerals can be recovered with current recycling processes.[17]

A global policy push on recycling

Driven by energy security concerns, countries around the world are boosting battery recycling with ambitious policies.

In Europe, the "EU Battery Regulation" mandates higher collection rates and efficient recycling processes.[18] The United States has introduced initiatives like the Battery Recycling and Critical Mineral Recovery Act to fund recycling programs and research.[19] China has implemented stringent recycling regulations and established a robust infrastructure for battery recycling.[20] We provide more detail in the next section.

Recycling economics are improving

Recycling economics are improving, thanks to rapid innovation and economies of scale.

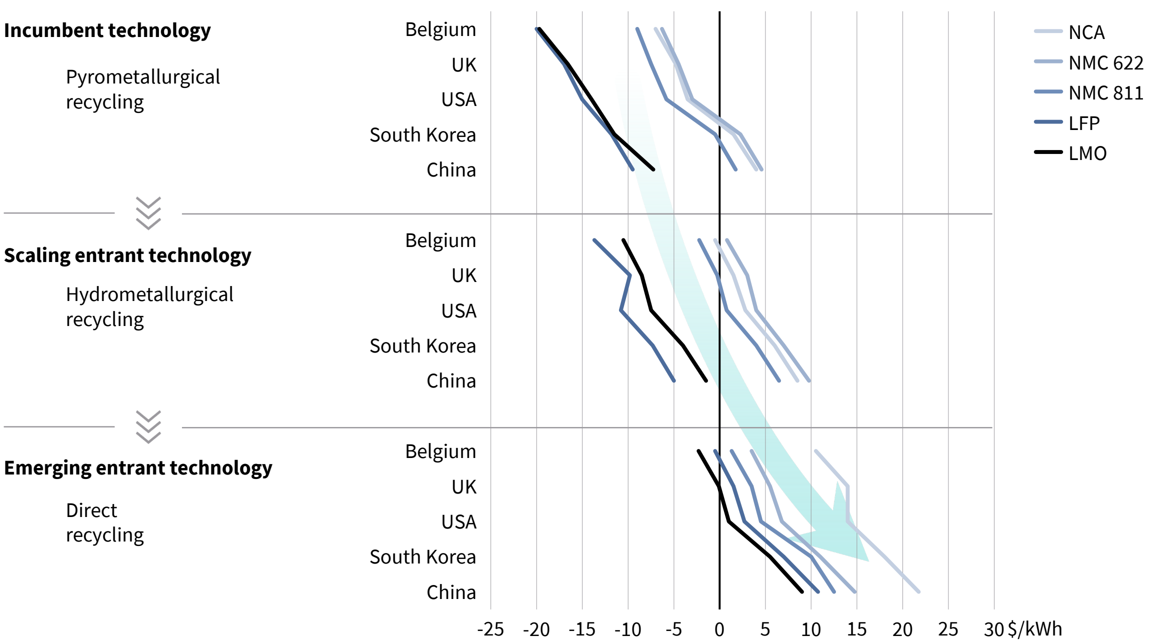
Recycling costs differ by region and chemistry, driven by different labor costs, standards, and subsidy schemes. As new, cheaper recycling processes develop, profitability rises.

Today, most battery recycling is done via a pyrometallurgical process — a high-temperature process to recover minerals. Newer hydrometallurgical processes — leveraging chemical solutions — tend to have better economics and hence are growing rapidly. Novel direct recycling methods will further improve competitiveness with a lower environmental footprint.

Beyond technology development, further cost reduction can be expected from rising recycling facility utilization as more batteries will start to retire. Today, recycling plants can run at utilization levels below 25%. As recycling is a capital-intensive business, higher utilization will lead to lower unit costs.

Although mining new minerals may seem to be more financially profitable than recycling for the foreseeable future, this advantage disappears when externalities are taken into account.[21] Mining does much greater environmental and societal harm, which, with the right externality pricing policies, can turn the economic case in favor of recycling. Thus, batteries will cost society less if they are recycled wherever possible.

Exhibit 9: Improving battery recycling economics, net battery recycling profit, by region, selected chemistries



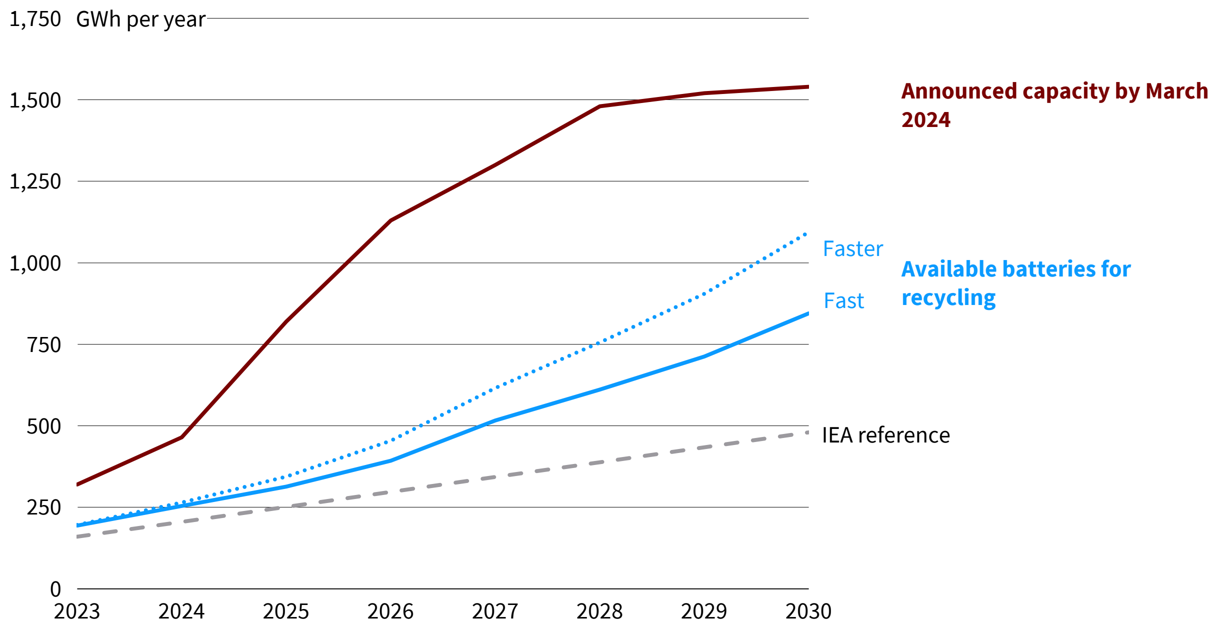
Note: NCA: Nickel Cobalt Aluminum; NMC 622: Nickel Manganese Cobalt (6:2:2 ratio); NMC 811: Nickel Manganese Cobalt (8:1:1 ratio); LFP: Lithium Iron Phosphate; LMO: Lithium Manganese Oxide.
Source: ETC Material and Resource Requirements for the Energy Transition (2023), Biswal et al. (2024), RMI analysis

Enough recycling capacity through 2030

As a result of a strong policy push and improving economics, battery recycling capacity is scaling up rapidly — currently well in advance of batteries reaching end-of-life.

As shown in Exhibit 10, the total announced battery recycling capacity today would be sufficient to recycle all available batteries at end-of-life through 2030, as well as all their production scrap. Hence, recycling at the current collection rate of about 60% should raise no near-term capacity concerns at a global level. Indeed, the ability to predict end-of-life battery quantities far in advance permits much smoother expansion of recycling capacity, with less financial risk.

Exhibit 10: Battery recycling capacity and availability of recyclable batteries



Note: Includes recycling of production scrap.

Source: IEA Global EV Outlook (2024), RMI analysis

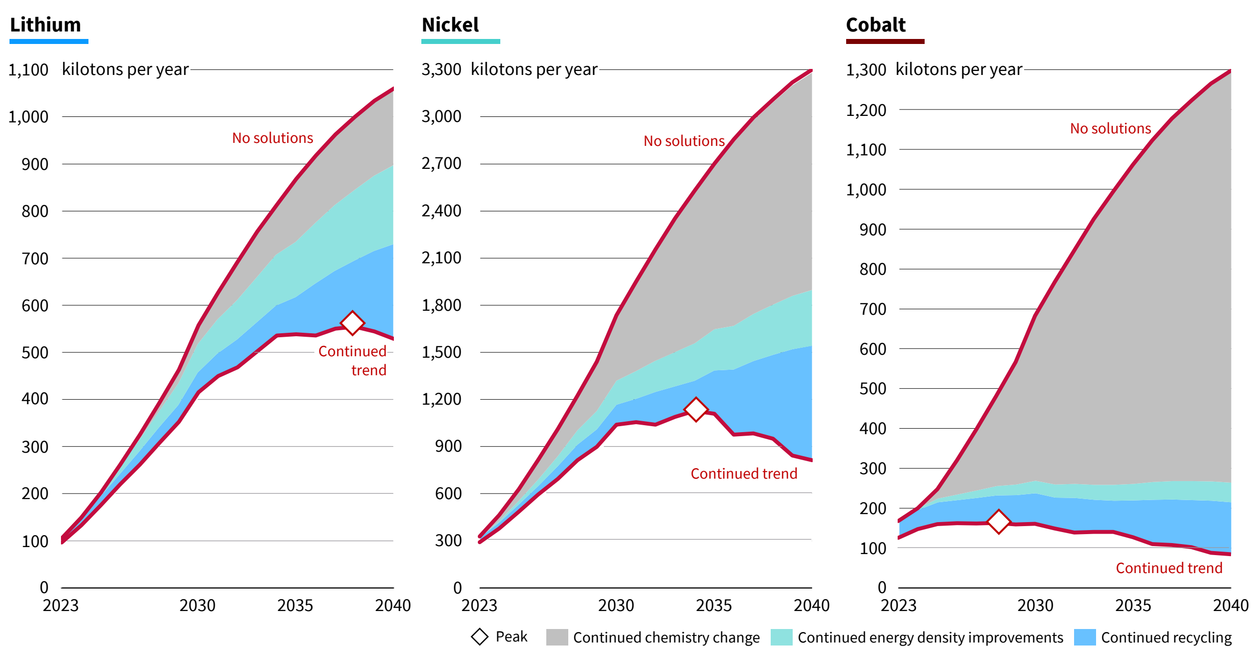
Peak mineral demand in the mid-2030s

Continuing the current trend means we face lower mineral demand growth than one might expect. As shown in Exhibit 11, the three continued trends — chemistry change, density improvement, and recycling — reduce 2030 mineral demand by about 25% for lithium, 40% for nickel, and 75% for cobalt (compared to a no solutions scenario). Some of cobalt's improvement also comes from the rise of the automotive sectors, which use chemistries that require less cobalt per battery cell than consumer electronics do.

After 2030, change will continue to curb mineral demand growth, leading to a peak in net demand for lithium in 2038, nickel in 2034, and cobalt in 2028 — all within a single battery lifetime.

Appendix B provides a more detailed analysis.

Exhibit 11: Net mineral demand under continued trends versus no solutions, fast battery uptake scenario



Source: RMI *X-Change Batteries*, RMI analysis.

Going faster leads to a higher peak and faster decline

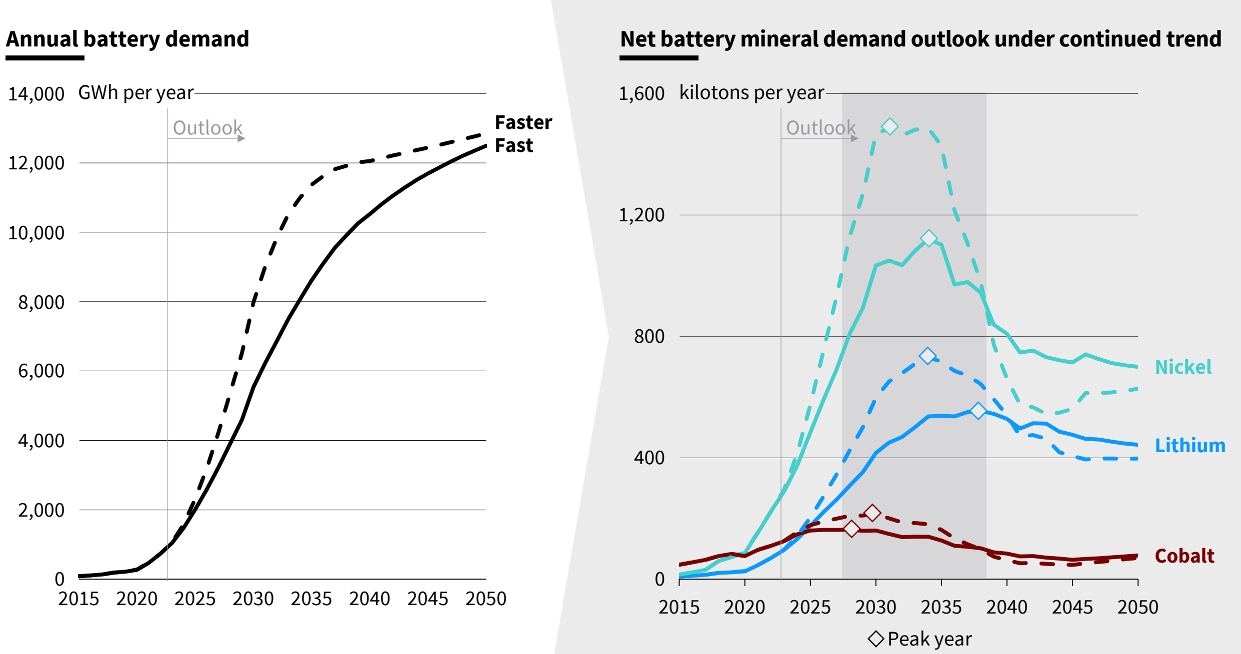
If the transition unfolds faster than in the above case, the mineral peak will be substantially higher while, in the case of lithium and nickel, moving closer by a few years.

Though battery demand is expected to increase by a factor of 8 to 11 by 2035, the net demand for key minerals will grow more modestly. Specifically, net demand will peak at just over 3 to 4 times the 2023 levels for nickel, just under 6 to 8 times for lithium, and only 1.3 to 1.6 times for cobalt.

After the peak, net mineral demand will start to decline as recycled materials outpace the growth of gross battery mineral demand, although the dynamics of the system imply that the curve takes many years to turn fully downward.

As we will see in the next section, demand may even reach net zero in the long term.

Exhibit 12: Battery demand and resulting mineral demand under continued trends



Source: RMI *X-Change Batteries*, RMI analysis

3. Accelerating the trend: net-zero battery mineral demand by 2050 is within reach

Change begets change, and action begets action. New innovations in battery production and recycling, along with renewed attention to efficiency and energy security, accelerate solutions to the battery mineral challenge.

This section shows what such an accelerated trend may look like, including all six solutions from Section 1. We analyze a faster change in chemistry mix, energy density, and recycling, as well as extending battery lifetimes and making both vehicles and transport systems more efficient.

We find that an accelerated trend can nearly halve peak lithium demand, while avoiding most of long-term demand and putting net-zero battery mineral demand by 2050 within reach.

The drivers of accelerated change

In this section, we provide a reasonable scenario for the six solutions that can accelerate the pace of change. Our estimates are often far more conservative than the full potential.

Exhibit 13: The drivers of an accelerated trend

A Changing chemistries
- Speed up sodium battery scaling in EVs

B Higher energy density batteries
- Raise learning rate to match top-tier battery level

C Recycling
- Raise collection rates
- Raise recovery rates to best-in-class
- Lower production scrap rate to best-in-class

D Reuse and extend lifetime
- Reuse transport batteries in stationary storage
- Extend lifetime of EV batteries

E Efficient vehicles
- Cut EV energy needs through better design efficiency and right-sizing

F Efficient mobility
- More modal shifting via electric micromobility, urban planning, active modes, and public transit
- Better freight efficiency

Accelerated battery chemistry mix change

The continued trends scenario is relatively conservative. It assumes no major scale-ups of emerging battery chemistries, only shifts among existing ones. The past decade has taught us to expect otherwise. Advanced energy storage may also emerge from technologies other than electrochemical batteries.

Novel battery chemistries have made rapid progress toward commercialization. Though many are still in a pre-commercial stage, sodium-ion chemistries are quickly approaching the mass market. In just the past year, several battery and car companies (including CATL, BYD, Northvolt, Farasis, JAC, and

JMEV) made significant product announcements that included sodium-ion batteries.[22] As new sodium batteries scale, demand for lithium, nickel, and cobalt will fall.[23]

Accelerated energy density innovation

As described in our previous report, *X-Change: Batteries*, the pace of energy density improvements of leading batteries is accelerating. Some improvements are making LFP batteries better than ever,[24] while others are using new designs to improve the usable energy per charge.[25]

This acceleration suggests that the average energy density could start rising faster as well, as the top-tier batteries of today are the average batteries of tomorrow.

Thus, the 6% learning rate under continued trends may well turn out to be a percentage point or so higher, as the average catches up to the leader.

Better recycling

As discussed in the previous section, policy for battery recycling is accelerating — led by China and the EU, as well as the United States more recently. These policies imply a likely acceleration in recycling rates.

On battery collection rates, for example, China's National Guidance for New Energy Vehicle Battery Recycling was implemented in 2018 and demands a 100% collection rate for EV batteries (like nearly all US states' requirement for lead-acid gasoline-car batteries), while complementary policies improve traceability and infrastructure.[26] Recent EU legislation will also increase collection rates for EVs and consumer electronics. And in the US and beyond, leading startups are scaling fast to realize the opportunity, including Ascend Elements, Green Li-ion, Li-Cycle, and Redwood Materials.[27] There is every reason to believe that collection rates can exceed the approximate 60% of the continued trends case and reach 90% or more.

Mineral recovery rates will improve as well. For nickel and cobalt, CATL in China claims it has already achieved a recovery rate of 99.6%.[28] For lithium, innovative companies have achieved recovery rates of 95% or more, including toZero and Renewable Metals, with commercial operations on track to begin soon. Direct recycling approaches, such as from Princeton NuEnergy, offer even better economics and similarly high recovery rates, though still at pre-commercial scale (as of spring 2024).[29] As these technologies rush to market, average recovery rates can be expected to rise from 80%–95% today to 95%–99% or more in the coming decade.

Longer battery lifetimes

There are many ways to extend battery lifetimes by reuse or better maintenance. From 2021 to 2024, progress on lifetime extension caused BNEF to increase projected battery lifetimes by an average of two years.[30] If progress continues to outpace expectations, we may well see another two-year increase, similar to findings in recent research papers.[31] Second-life batteries are also projected to grow, becoming a $7 billion market within a decade.[32]

Efficient vehicles

In the race to more affordable EVs, automakers are redesigning vehicles from top to bottom. For example, a recent EPRI and NRDC study found that continued advances in US EV efficiencies could halve the electricity consumption per mile by 2050.[33] As this trend accelerates, per-vehicle battery demand could drop nearly 30% by 2030, as outlined in the latest IEA Global EV Outlook.[34]

This is just a fraction of the technoeconomic potential. BMW profitably sold the 2013–2022 *i3* at quadruple typical vehicle efficiencies — while multiple startup designs would bring deeper improvements if commercialized.[35] So would the Mercedes 2022 *EQXX* concept EV,[36] which is 87% more efficient than a standard-range Tesla *Model 3.*

Efficiency improvements could also come from vehicle right-sizing, where there is ample room to improve. Popular sedan models are 44% larger than they used to be, while popular pickup trucks are 75% larger.[37] US cars gained weight faster than their drivers, but surely the drivers didn't balloon that much. Moreover, SUVs' share of EV sales has doubled or tripled, from 20%–25% to 50%–75% (across different regions), in just five years.[38] Even just returning to recent, lower SUV sales shares could satisfy our accelerated scenario, compared to a persistently high share under continued trends.

Efficient mobility

Further upstream, more efficient mobility can significantly curb mineral demand for trucks and cars. In countries like the United States, an average freight mile sees the truck less than half full.[39] Logistics optimization and digitization are helping companies rapidly improve their truck utilization, reducing the total number of trucks needed to move the same goods.

For passenger vehicles, ambition is turning into action as global cities accelerate land use reform. After just five years of transformative policies, Paris has transformed into a city that now sees many more trips by bike than by car, both inside the city and from the city center to suburbs.[40] Much more is possible in developing countries, where smart design during new infrastructure buildout can provide major benefits.[41] As usual, it's easier to build things right than to fix them later.

Even in the United States, RMI research has found that sizable reductions in vehicles miles traveled (VMT) are possible,[42] impactful,[43] and necessary to reach climate goals.[44] Enacting land use reforms can deliver more climate impact than half the United States ramping to 100% zero-emissions passenger vehicle sales by 2035.[45]

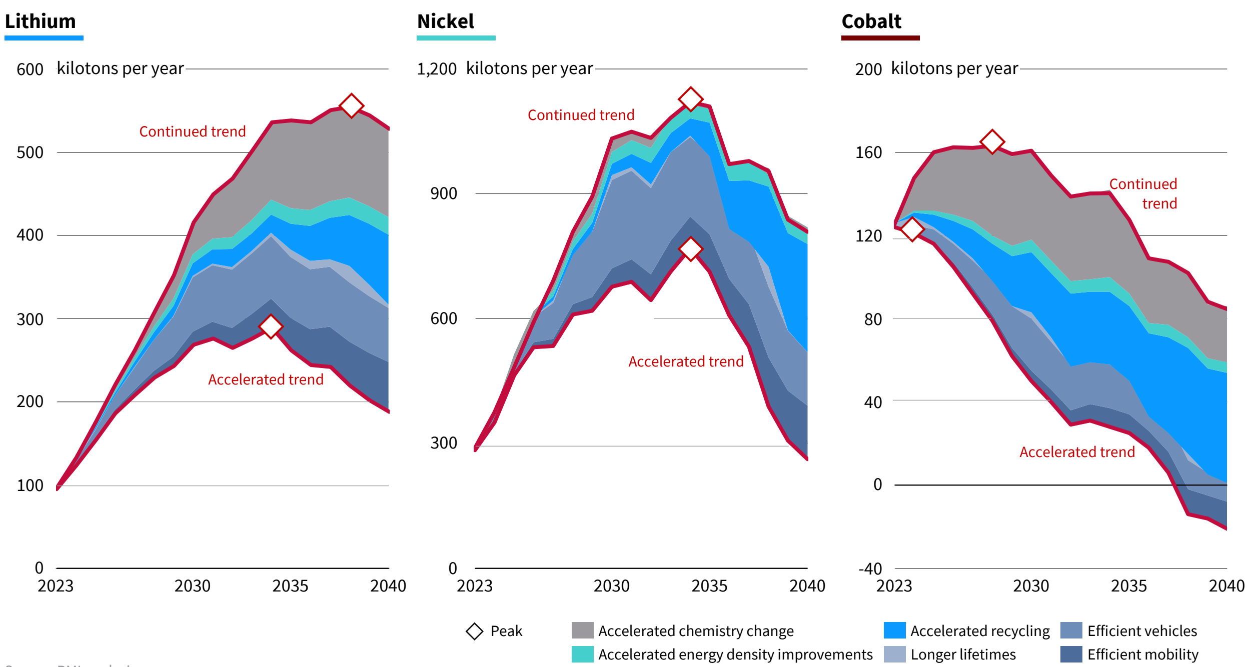
Successful actions will lead to lower car and truck demand — with reductions of approximately 15%–20% possible by 2050 based on analysis by the International Council on Clean Transportation (ICCT).[46]

Impact of each solution by decade

As shown in Exhibit 14, each of the six solutions affects battery demand by different amounts and in different decades.

- Short-term solutions to 2030: the most immediate solutions are faster chemistry change and more efficient vehicles. These two solutions can reduce the 2030 lithium demand by 100 kilotons per year.
- Medium-term solutions for the 2030s: chemistry change and vehicle efficiency remain the dominant levers, but recycling improvements and efficient mobility also start to contribute.
- Longer-term solutions for 2040 and beyond: recycling takes over as the dominant solution as more batteries reach end-of-life. Together with continued improvements in battery energy density and in vehicle and mobility efficiencies, most of potential virgin mineral demand can be avoided.

Exhibit 14: Net mineral demand of continued versus accelerated trend, fast battery uptake scenario



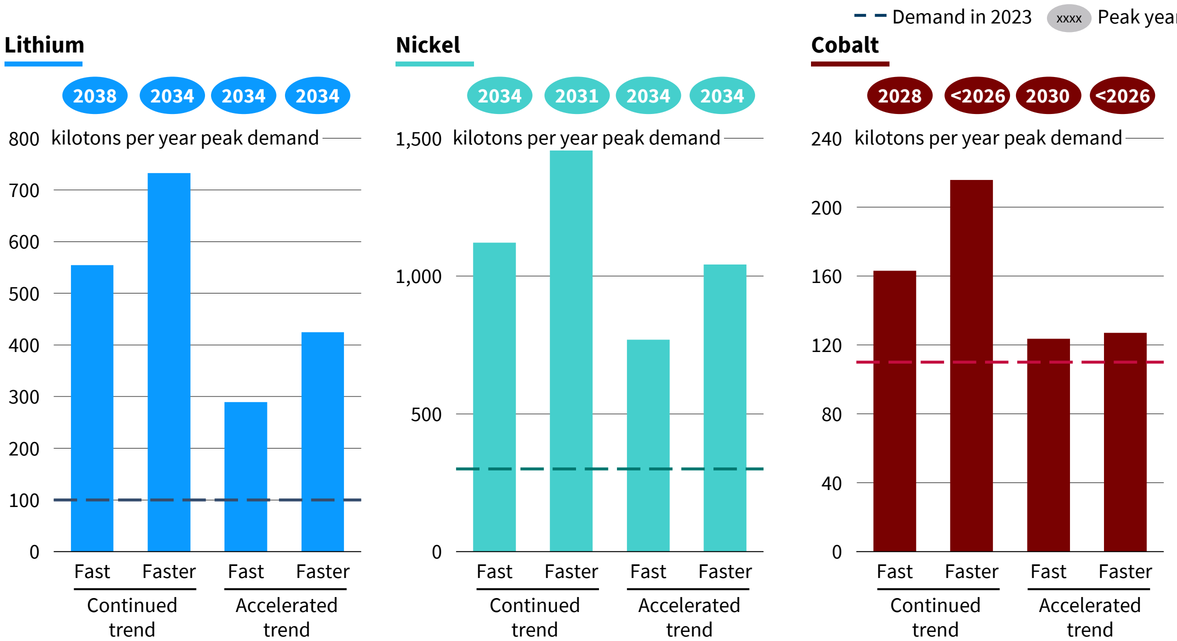
Source: RMI analysis

A lower peak in mineral demand

As more solutions get deployed sooner, mineral demand will peak earlier and at a lower level.

The accelerated trend results in a 46% lower lithium peak, at less than three times current demand. Similarly, peak nickel demand is 31% lower at 2.5 times current demand. Under the accelerated trend, cobalt demand may even peak near today's levels.

Exhibit 15: Net mineral demand peaks



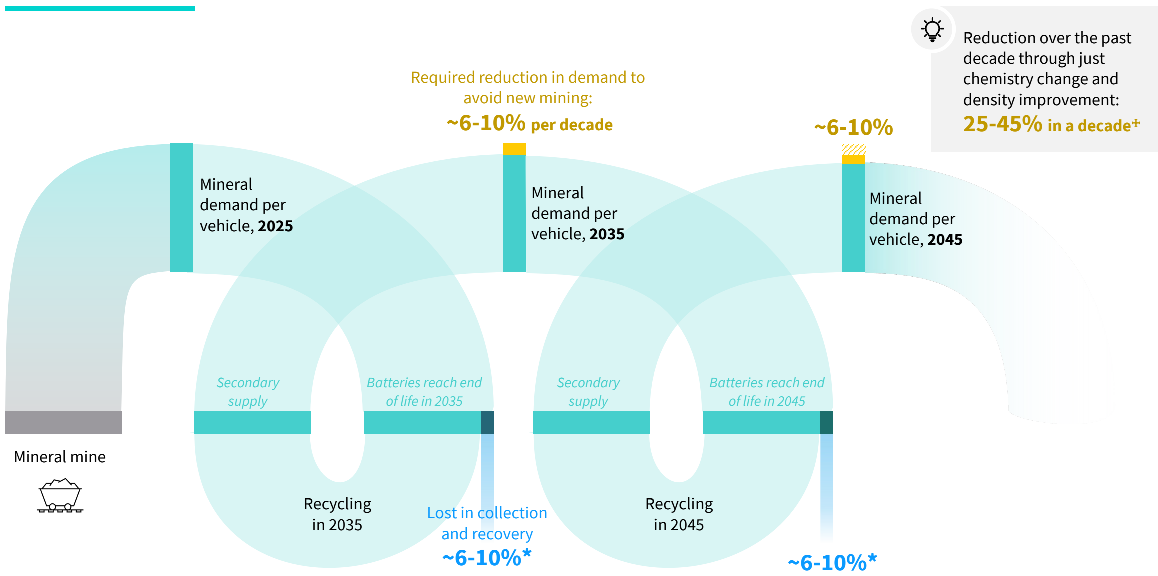
Source: RMI analysis

Approaching net-zero battery mineral demand by 2050

After peaking, battery mineral demand will continue to decline.

As annual battery demand reaches its maximum, losses in the collection and recycling recovery system can be offset by reduced mineral demand per battery due to efficiency and innovation. We illustrate this in the exhibit below. For example, if we collect 95% of batteries for recycling and recover nickel at 99% efficiency (under the accelerated case), we achieve a net recovery rate above 94%. This means that over a battery's lifetime, which can be more than a decade, solutions need to curb demand by just 6% to offset recycling losses. To put that in context: over the past decade, vehicle unit nickel demand dropped by almost 45%.

Exhibit 16: The battery mineral loop



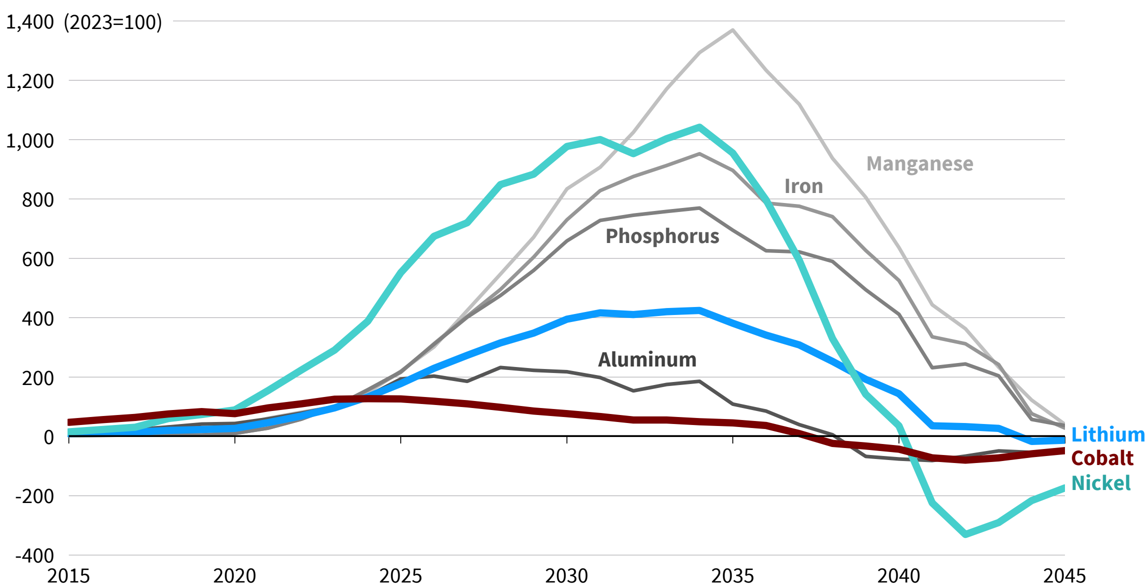
Note: Useful battery lifetime of a decade is indicative; lifetimes are likely longer.
* Accelerated case
+ *About 25% for lithium, about 50% or more for nickel and cobalt*
Source: RMI analysis

In our faster energy transition scenario, we rapidly approach maximum annual battery demand in the mid-2030s. Within a decade, an equilibrium sets in between mineral demand and mineral recycling, leading to a net mineral demand around zero by the mid-2040s.

Minerals beyond lithium, cobalt, and nickel can also reach net-zero demand. With enough policy support to overcome economic barriers, other materials may get recycled as well, leading to a peak and decline to net-zero demand before 2050. The story is similar for non-cathode materials such as graphite, as most of the six solutions cover the full battery and there are other improvements underway in anode chemistry to reduce graphite dependence.[47]

Companies are starting to reach the same conclusion: Robin Zeng of CATL recently stated that China is on track to reach zero mineral mining demand by 2042 due to its rapidly growing recycling market.[48]

Exhibit 17: Net mineral demand for cathodes (demand minus recycled supply), Faster scenario under accelerated trend



Note: Assumes recycling of all minerals in batteries.
Source: RMI analysis

4. The implications of meeting the battery mineral challenge

In this section, we explore the implications of successfully scaling the six solutions.

Meeting the battery mineral challenge will turn near-term mining into a one-time effort. As demand centers transform into supply hubs, and recycling offsets the need for new materials, countries can shift from oil dependence to circular independence, while gaining health and equity benefits that are maximized with systemic action. While China is leading the charge, the West is working to catch up, and the Global South stands to benefit from the vehicles that reach end-of-life there.

Making mining a one-off effort

Before full circularity is achieved in the accelerated trends scenario, an additional ~5 million tons of lithium, ~11 million tons of nickel, and ~0.7 million tons of cobalt will need to be mined between today and the 2040s.

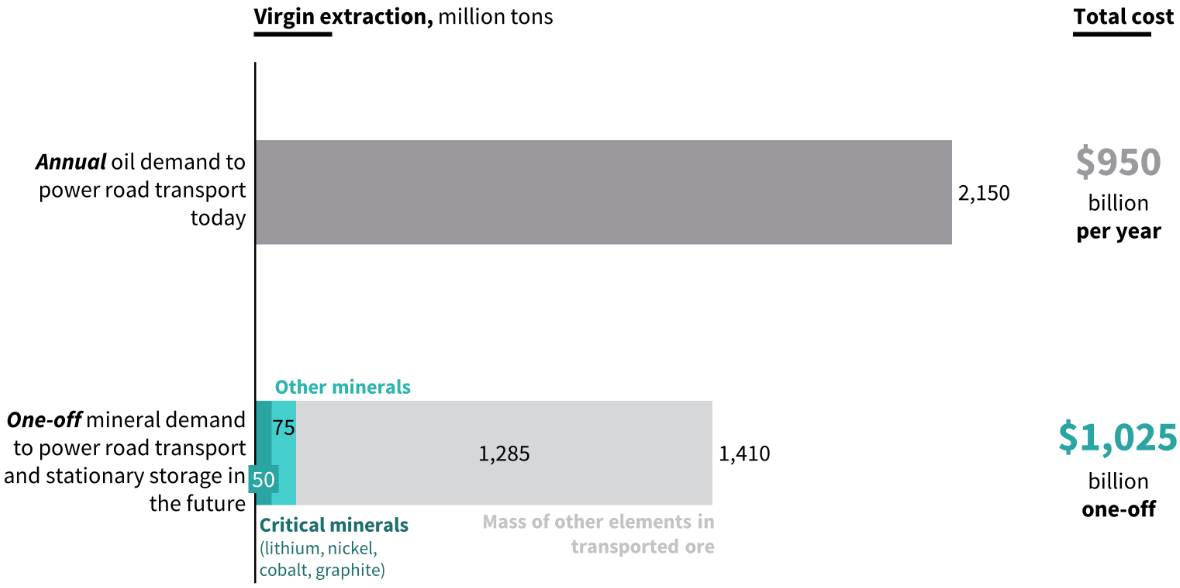
After adding the total manganese, aluminum, iron, phosphorus, graphite, sodium, copper, and other minerals that go into a battery, we need about 125 million tons of minerals to be extracted before we reach circular self-sufficiency. The total value of these minerals is roughly $1,080 billion at today's prices, or on average about $50 billion per year through the mid-2040s.

To put that into context, the batteries that contain these minerals will enable the phase-out of internal combustion engines in road transport. Every year, these engines consume over 17 times more tons of oil (2,150 million tons per year) than the amount of battery minerals we'd need to extract just once to run transportation forever. Even when including the weight of other raw materials in ore and brine, one-off mineral demand would still end up over 30% lighter than annual oil extraction for road transport. And unlike minerals, oil products are promptly burned in internal combustion engines and must be replaced each year, forever.

The mined minerals can keep being recycled while demand declines through innovation and efficiency. After reaching circular self-sufficiency, little to no mining is needed to sustain the system. Most of the minerals mined in the coming decades will still be recycled and reused in our energy system hundreds of years from now, much like our existing stock of precious metals.

That means the next two decades of mining for battery minerals can become a one-off effort, yielding the minerals that will not just power our energy and mobility system by 2050 but will continue to do so through to 2100 and beyond.

Exhibit 18: One-off battery mineral demand in context



Note: Calculated under Accelerated trends. Mass of other elements in transported ore are based on the typical mineral concentration of products leaving the mining site — i.e., after typical on-site concentration of natural ore. Cost is calculated based on current wholesale prices for extracted products; no refining or other costs are included.
Source: IEA *Global Critical Minerals Outlook* (2024), USGS National Minerals Information Center, RMI analysis.

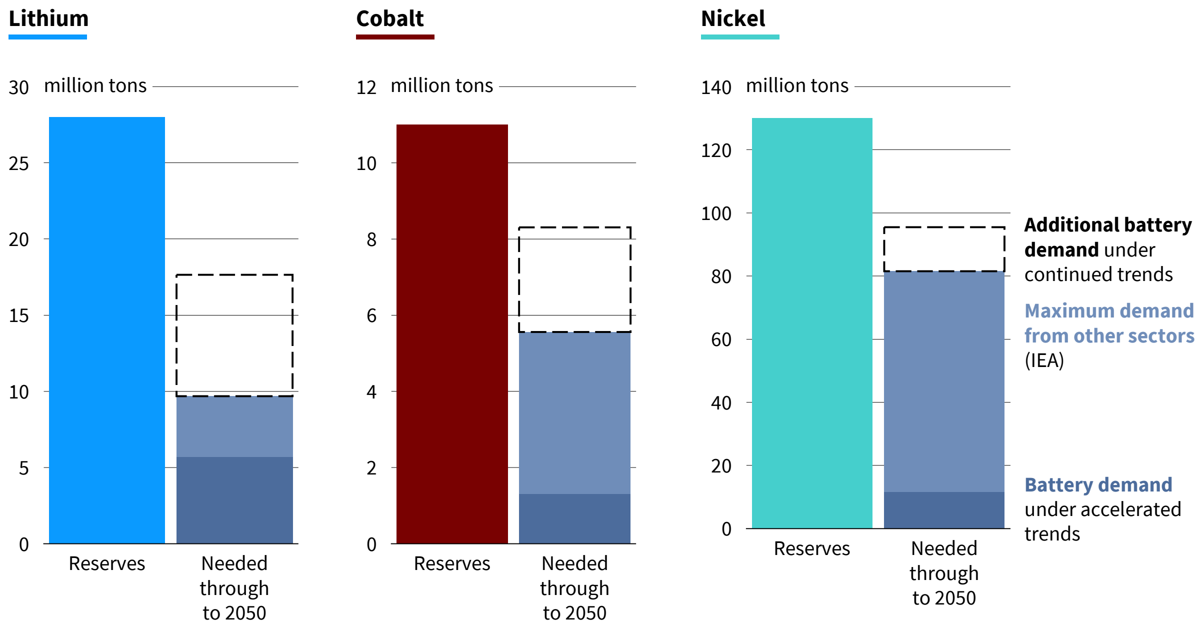
Share of global reserves

The total lithium, cobalt, and nickel needed to reach circular self-sufficiency is only a small share of total estimated reserves globally.

Under the accelerated trend, we only need to mine less than 40% of current lithium reserves, 50% of cobalt, and 60% of nickel for the battery sector to reach self-sufficiency. This includes additional mineral demand from other sectors, which may turn out to be much lower if similar deep circularity and efficiency solutions are pursued. We did not assess that in this report.

Even under the continued trend scenarios, total lithium, cobalt, and nickel demand through 2050 all fall well below total reserves. As shown in Appendix E, there is good reason to believe that total reserve estimates will continue to rise as well. So far, the harder we looked for these minerals, the more we found.

Exhibit 19: Total mineral need versus global reserves



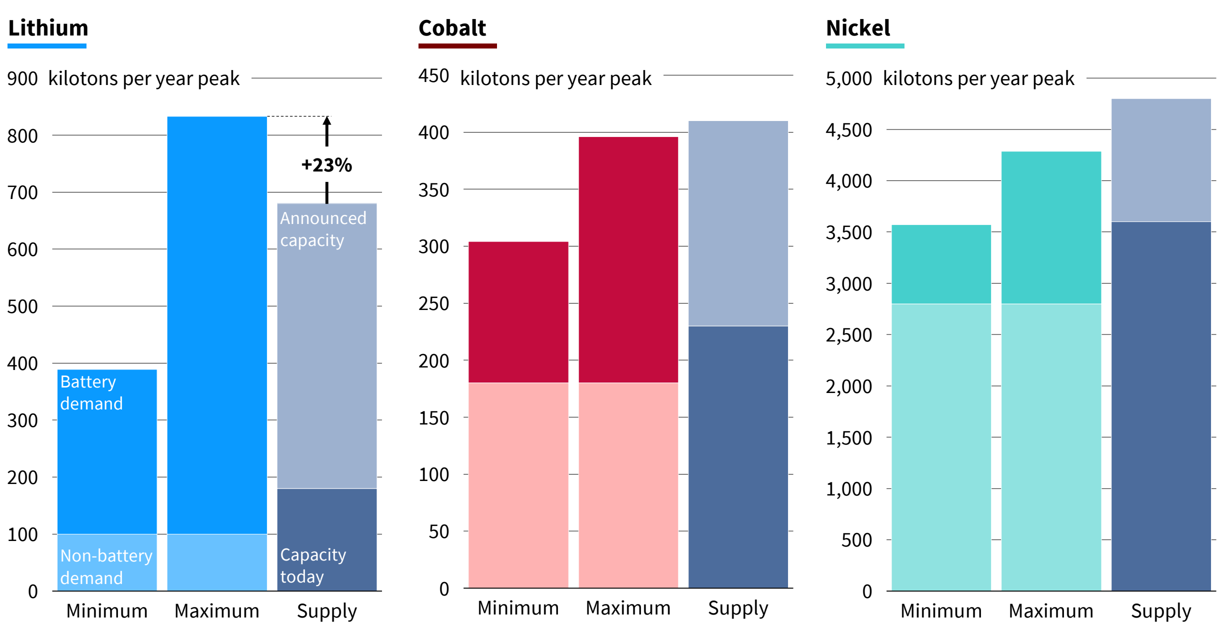
Source: IEA *Global Critical Minerals Outlook* (2024), USGS National Minerals Information Center, RMI analysis

Meeting peak demand

As shown in Exhibit 20, announced mining projects already get us most of the way to peak demand. Only in the Faster battery uptake scenario under continued circularity trends does demand outpace announced supply for lithium (by some 23%). There seems to be no gap for nickel and cobalt.

We still have about a decade to go before we hit peak demand around 2035, so we have ample time to fill in any gaps. As shown in Appendix E, is it highly likely we will be able to.

Exhibit 20: Peak net mineral demand versus announced mining supply



Note: Minimum represents the Fast scenario under accelerated trends; the maximum represents the Faster scenario under continued trends.

Source: IEA *Global Critical Minerals Outlook* (2024), USGS National Minerals Information Center, BNEF Battery Minerals Supply and Demand (2023), RMI analysis

From oil dependence to circular independence

Under the accelerated trends scenario, almost all mineral demand from the mid-2040s onward can be met with recycled content from batteries reaching end of life. As the world shifts from mining rocks to mining end-of-life batteries to collect minerals, large battery demand centers will attract recycling capacity and become supply centers.

In the long term, a circular battery system is a big step toward total energy independence. And the more that efficiency and innovation can curb mineral demand, the easier it will be to reach this state.

About 80% of world nations (by population) are net oil importers.[49] Their oil dependency poses a constant, imminent risk to their economy as it requires a continuous stream of imports. If oil imports stop, most countries would face immediate paralysis.

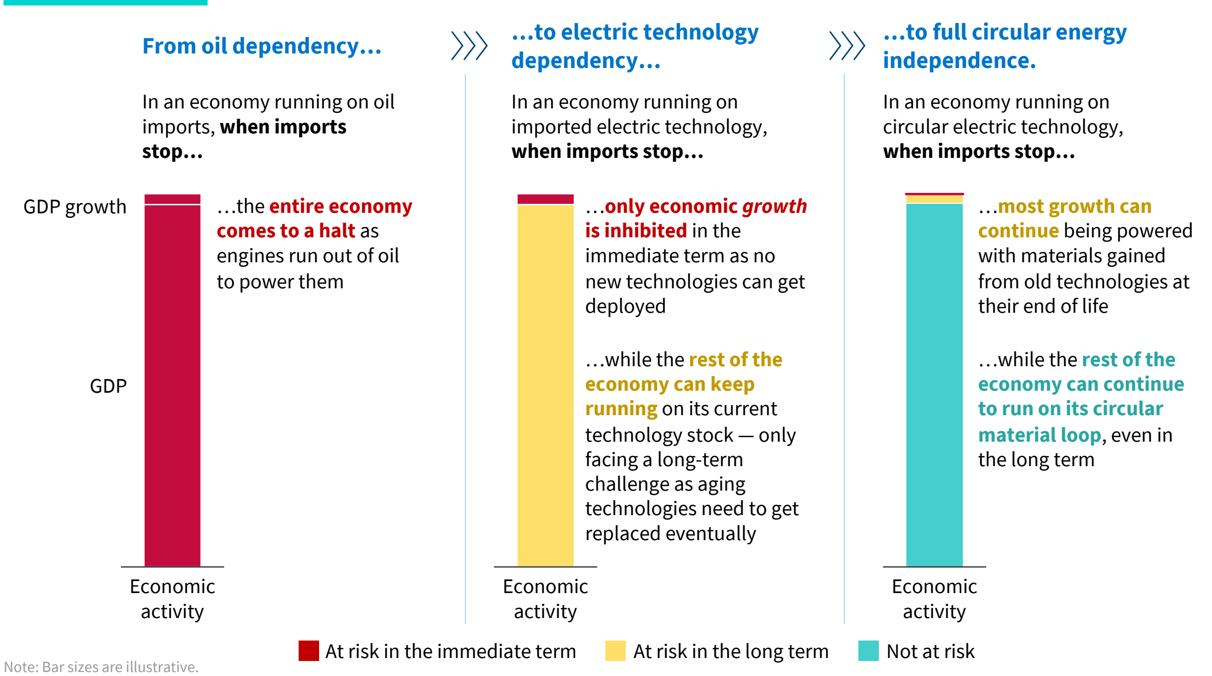
Transitioning to EVs powered by renewable energy reduces this risk significantly. While many countries might still be net importers of solar PV, batteries, and battery minerals, this dependence is only crucial for technology replacement and growth, not day-to-day operations.

A circular technology system eliminates this residual dependence by enabling domestic recycling of materials. This can mitigate most of the replacement risk and even derisk growth, leading to near-total energy independence.

This means battery recycling has the potential to become a key geopolitical tool to reshore or friendshore supply, regardless of the location of geological mineral deposits, and to improve global security and stability.

Countries have started to recognize this benefit, making aggressive recycling policy as laid out in sections 2 and 3, kickstarting a race to the top on battery circularity.

Exhibit 21: From oil dependency to circular energy independence



Note: Bar sizes are illustrative.
Source: RMI analysis

A circularity race to top

China is leaping ahead of other countries — building out battery recycling capacity at breakneck pace. As shown in Exhibit 22, China's near-term recycling capacity addition plans dwarf those of the EU and United States in the coming years.

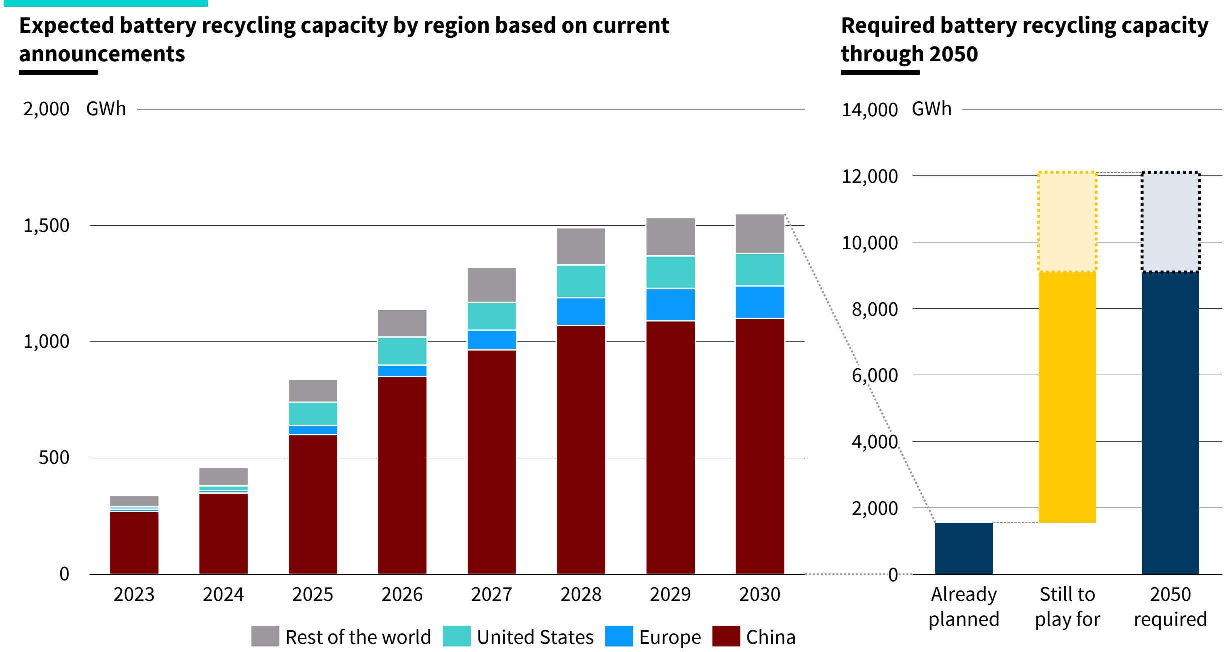
Other countries risk falling a step behind, focusing on yesterday's debate of who owns the mines and who gets to build the batteries, instead of who gets to derive the most value from the batteries through efficient and prolonged use, and who gets to recycle them in the end.

Through efficiency and recycling, the West — behind in the mineral race today — is given a golden opportunity to stage a comeback and become mineral-independent in the 2030s. It is not sitting on its hands, but is rapidly developing new battery circularity policies.

There is still a lot to play for; today, only 1.5 out of the 9 to 12 TWh per year in recycling capacity needed in the long term is planned for. We are less than one fifth into the race.

Recycling batteries will take more than just building recycling centers. Other infrastructure is needed for collection and sorting. And domestic refining and manufacturing is essential to turn recycled minerals into local batteries.

Exhibit 22: Battery recycling capacity outlook



Source: IEA *Global EV Outlook* (2024), RMI analysis

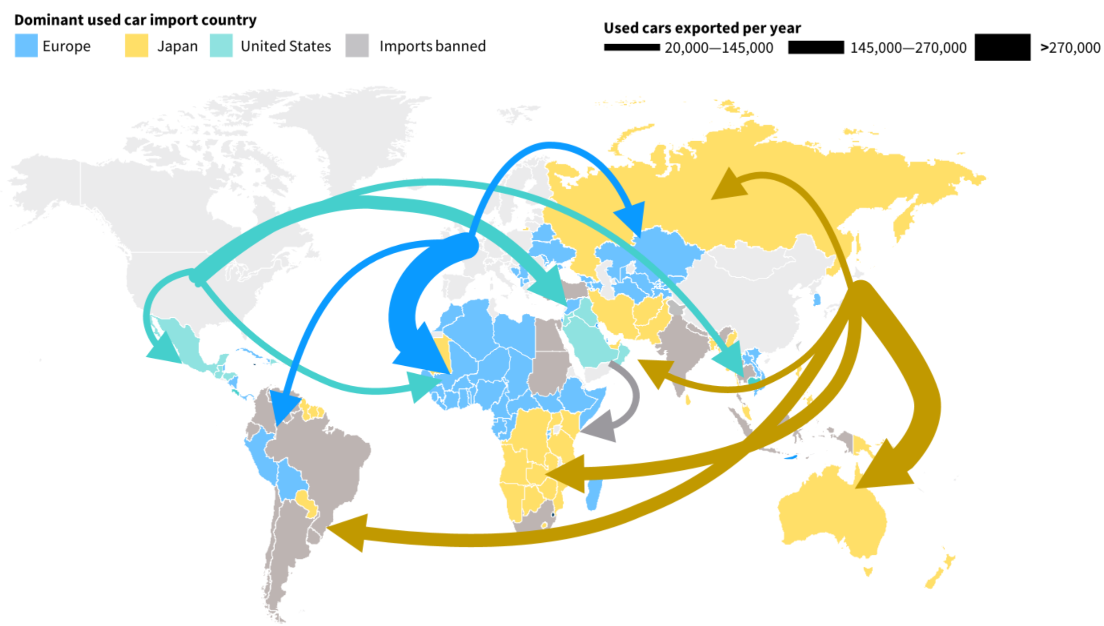
The Global South can play an outsized role

Many vehicles end their life in the Global South as second- or third-hand cars, creating a unique chance for these regions to capitalize on the battery recycling value chain.

As shown in Exhibit 23, the UN estimates that millions of second-hand cars are exported from the Global North to the Global South each year. Once car fleets shift to EVs, this influx of old battery-powered vehicles can be used to set up a robust recycling industry from vehicles that reach their end of life, allowing for job creation, economic growth and geopolitical leverage over the battery supply chain.

Battery manufacturing and mineral processing capacity is already growing in parts of the Global South, such as in Morocco, Indonesia, Chile, Argentina, and Brazil.[50,51,52] Establishing recycling facilities nearby is a logical step to optimize efficiency and support local industries.

Exhibit 23: Used car trade flows



Source: UNEP *Used Vehicles And The Environment* (2017)

Upstream solutions boost downstream success

Meeting the battery mineral challenge will mean pulling all levers at our disposal. Rapid roll-out of upstream solutions will maximize downstream success.

For example, we may not need to build as much recycling capacity if we promote better urban planning and mode shifting, which can reduce car sales and hence battery demand. Such an approach avoids overbuilding mitigation measures.

From upstream to downstream, the six solutions are best sequenced as follows:

1. **Efficient mobility** — reduce the amount and type of vehicles needed.
2. **Efficient vehicles** — use fitter designs and right-sizing to reduce the battery capacity needed per vehicle.
3. **Changing chemistries** — ensure that the most resource-efficient batteries are used in each application.
4. **Higher energy density batteries** — drive innovation of each chemistry to improve the energy density.
5. **Reuse and extend lifetime** — ensure that the batteries in each vehicle can be used for as long as possible, through better operation and maintenance or reuse.
6. **Recycling** — when batteries finally reach end-of-life, recycle their materials.

It must be noted that these first five steps only reduce or delay mineral demand, and only the addition of the final step — recycling – will make the battery system circular. In the long term, recycling is the most impactful lever for curbing virgin mineral demand.

Deeper efficiency brings greater benefits

Combining better batteries with more efficient vehicles and mobility can maximize societal benefits for emissions, equity and human rights, security, health, and much more.

Though EVs already have much lower life-cycle emissions than combustion cars,[53,54] efficiency and circularity can drive down emissions much further. Recycling can save a third or more of battery production emissions,[55] with further improvements from energy density, reuse, and vehicle efficiency (which also requires less energy per distance). More efficient mobility can eliminate further emissions, including in buildings and land use from smarter city design.[56]

The six solutions can also help to address global human rights and equity concerns. Curbing oil demand reduces the inequities of fossil fuel pollution and its climate impacts,[57] while curbing mineral demand can avoid harmful labor practices such as in cobalt mining[58] (where projected demand has been halved by just three years of innovation).[59] Efficient mobility can strengthen equity in other ways, as public transport and active modes are disproportionately used by low-income communities across the world.[60,61,62,63]

Achieving a circular energy system will also avoid dependencies on both oil and minerals, as mentioned in the previous sections. Recent research suggests that demand-side policies are among the most powerful levers to maximize energy security.[64]

Finally, the six solutions can benefit health in several ways. Air pollution has been named the leading contributor to global disease burden[65] — and more than 5 of its 8 million annual deaths have come from the burning of fossil fuels.[66] Switching to EVs already reduces that number substantially. More efficient (and smaller) vehicles will also save lives for pedestrians, as large vehicles are 45% more likely to cause fatalities in pedestrian crashes.[67] And recent health studies have found even more health benefits from active mobility.[68]

There are many more benefits — from water and land use reductions to the protection of biodiversity — which can only multiply as well.

Exhibit 24: Compounding benefits of an efficient, circular battery and transportation system

Measure	Emissions	Equity	Security	Health
Switching to EVs	**Avoided emissions from tailpipes and upstream oil** (~20% of global emissions)	**Fewer fossil fuel harms**, such as disproportionate impacts of pollution and climate disasters	**Lower dependency on oil and gas imports** for the 80% of countries that are net importers	**Cleaner air**, as roughly 5 of 8 million annual pollution deaths come from fossil fuels
More efficient vehicles and circular batteries	**Avoided emissions from battery production** and global transport of materials	**Reduced mining harms,** such as displacement and human rights violations	**Lower mineral dependency** on countries that host most of the critical battery minerals	**Safer vehicles**, as larger vehicles lead to more pedestrian deaths
More efficient mobility	**Avoided emissions from vehicle life cycle and system** (with more efficient buildings and land use)	**Better mobility access,** as vulnerable populations are more likely to use alternative modes of transport	**Lower dependency on critical infrastructure**, as less of the economy depends on grids, roads, and other infrastructure	**Active mode benefits**, which can sometimes improve health even more than cleaner air

Further upstream; deeper efficiency intervention

Compounding benefits

Actions toward circular self sufficiency

Progress will not happen by itself; action is needed across the value chain. Different actors can accelerate change across the six solutions, from upstream to downstream:

- Efficient mobility can be directly advanced by governments, which can improve urban planning and infrastructure for alternate modes of travel. Electric micromobility companies are also key, particularly in urban areas and developing economies.
- More efficient vehicles will come from car companies with the help of governments, given the need to set ambitious targets and ramp up innovation. Reducing battery needs (for a given range) can also help to overcome EV profitability concerns, as in the case of the BMW *i3* and Tesla *Model 3*.[69,70]
- The development of new chemistries and higher energy density is driven by battery researchers and manufacturers, who, with ample government and private support, can accelerate the pace of innovation while designing for traceability and circularity.

- Extended battery lifetimes and second-life use will benefit from policy standards, as well as markets to improve diagnostics, warranty frameworks, and battery management systems.

- Recycling also involves a combination of actors. Governments can provide a clear demand signal by setting standards for collection, recovery rate, traceability, and recycled content. Voluntary markets can also use green premiums to improve recycling revenue as well. Meanwhile, innovators can work to scale novel methods — particularly those that can reduce environmental burdens and improve economics via higher recovery rates and lower capital costs. Many more recommendations can be found in other RMI research.[71]

Exhibit 25: Solutions, actions, and actors across the value chain

Value chain	**Mining and processing**	**Battery manufacturing**	**Vehicle manufacturing**	**Mobility applications**	**Second-life battery use**	**Battery recycling**
The six solutions		Changing chemistries; Higher energy density batteries	Efficient vehicles	Efficient mobility	Reuse and extend lifetime	Recycling
Key actions	**Markets:** transition business models from mining to recycling **Policy:** incorporate cost of externalities into policy reforms	**Markets:** Incorporate traceability software and design for circularity **R&D:** accelerate battery innovation on cost, performance, and environmental footprint **Funders:** support R&D efforts to improve technology and economics	**Markets:** unlock lower cost EVs by right-sizing and designing for circularity **Policy:** incentivize right-sizing by setting ambitious efficiency standards across vehicle types	**Markets:** scale efficient freight practices and electric micro-mobility **Policy:** reform land use and scale infrastructure to enable mode shift, particularly for new development	**Markets:** innovate on diagnostics, insurance and warranty frameworks, and battery management systems **Policy:** incentivize re-use or set longer lifetime standards	**Markets:** scale new technologies and improve economics; co-locate recycling infrastructure with battery processing **Policy:** incentivize or set standards for collection, recovery rate, traceability, and recycled content

A lot of room to go faster

We can develop all six solutions faster and more effectively than our current analysis assumes.

For example, on novel chemistries, we conservatively exclude pre-commercial technologies beyond sodium-ion, and we hold chemistry mix constant after 2035 — but innovations could come faster and deeper to displace critical minerals even more.[72]

On energy density, the rate of improvement has accelerated in recent years[73] — and if those recent trends continue, average density might improve even faster than we assume.

On recycling, collection efficiencies are high but there is always room to reach 100%, as China regulated for EVs in 2018.[74] Circular Energy Storage believes we may have already hit 90%.[75]

On battery lifetime, research papers such as the previously mentioned one by Gaines et al. (2023) assume even longer battery lifetimes than we do, as well as more second-life uses in sectors beyond grid storage — particularly for LFP batteries that are becoming more and more popular worldwide.[76]

On vehicle efficiency, recent analyses show that EV efficiency could increase nearly 2.5-fold by 2050,[77] or even 3–6-fold if today's state of the art spreads more widely — implying that we can achieve deeper long-term improvements than the IEA scenario's modest reduction in battery kilograms per car.[78]

And on efficient mobility, analyses by Riofrancos et al. (2023)[79] and the ITDP's Compact City Scenario have even greater estimates for battery vehicle demand reductions from urban planning and mode shift.[80]

It is clear that our accelerated trends case is by no means the upper bound of what is possible. We may well exceed it, especially as the benefits of an efficient and circular battery system start to manifest in real life, and the circularity race to the top intensifies.

The opportunity is clear. Now, it is up to policymakers and the market to seize it.

Managing the volatility to come

We end, however, on one note of uncertainty. Mineral prices are highly volatile: in recent years, rare earths, lithium, nickel, cobalt, and even in part copper, have seen soaring and then crashing prices. Yet mining companies require manageable volatility, with average prices adequate to sustain exploration, production, and cleanup. If the six solutions' combined progress is anywhere near as strong as we present here — and we think it's likelier to overperform — then future critical-metals values and prices would be expected to decline.

That could make the system ring like a bell, with fewer new mines (fitting lower future demand) but also less incentive to recover and recycle batteries (mitigated by cheaper recycling and, if needed, by stronger incentives or rules to ensure high recovery and recycling). In other words, the high-demand, high-price, high-mining scenarios originally assumed by most policymakers are likely to be reversed, but along the way, considerable volatility and disruption can be expected. Policymakers would do well to focus on how to make that future happen and how to help mitigate its financial risks and disruptions, so that all market actors, including mining companies, can more easily and happily invest in the circular future rather than fighting to protect the old.

Appendices

Appendix A: Modeling demand for battery minerals

Appendix A describes our modeling for the battery mineral outlooks that underpin this report.

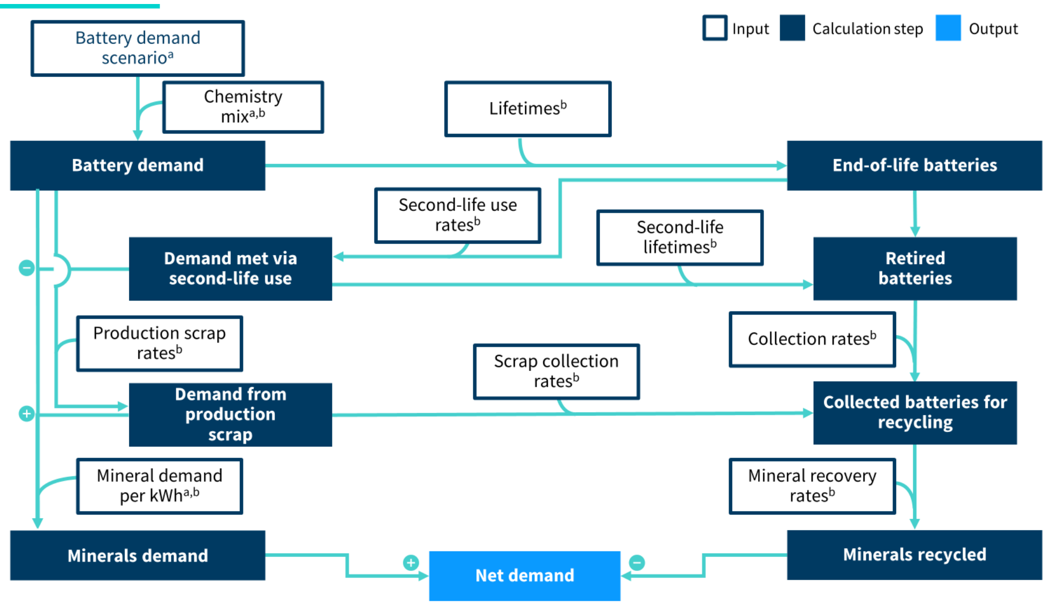
Total mineral demand is based on sectoral battery demand (from RMI *X-Change Batteries*[81]), sectoral chemistry mix (from BNEF's *Long-Term Electric Vehicle Outlook* [2024][82] until 2035 and held constant thereafter, with RMI estimates for consumer electronics), and cathode mineral mass-per-energy conversions for each chemistry (from BNEF, IEA's Global EV Outlook [2024],[83] and RMI research). The BNEF chemistry outlook uses more than 20 distinct battery chemistries, though it does not currently include solid-state batteries or other non-commercial technologies.

Total recycling volumes are calculated based on assumed battery lifetimes (for each sector and chemistry), recycling collection efficiencies (for each sector), and recycling recovery rates (for each mineral). All these parameters use BNEF's Lithium-Ion Battery Recycling Availability Tool (2024),[84] with additions from Gaines et al. (2023)[85] for consumer electronics. Because we use whole-number lifetimes that increase over time, we smooth any "skipped" retirement years by splitting the prior year's retirements between that prior year and the "skipped" year.

We also include estimates of second-life battery applications, which delay demand as well as recycling availability. We follow BNEF to assume that all second-life uses are for grid storage, with no reuse from consumer electronics. We then calculate the amounts based on the fraction of retired batteries that are available for second-life use (by sector and chemistry) and second-life lifetimes from BNEF and Gaines et al. (2023).[86] If a chemistry's grid storage demand is entirely met by second-life batteries in that year, we allocate any remaining available second-life batteries to other chemistries in that year. If second-life-eligible batteries are not used, they are retired after their first life as normal. If batteries are used in second-life applications, they are retired after their second life as a grid storage battery.

Finally, we include BNEF estimates of production scrap rate and Gaines et al. (2023) estimates of recycling collection efficiency for scrap.[87] We assume that scrapped batteries are available for recycling collection in the year in which they are scrapped.

Exhibit 26: Flow chart for battery mineral demand model



Sources: (a) RMI, (b) BNEF Lithium-Ion Battery Recycling Availability Model (2024) & Gaines et al. (2023)

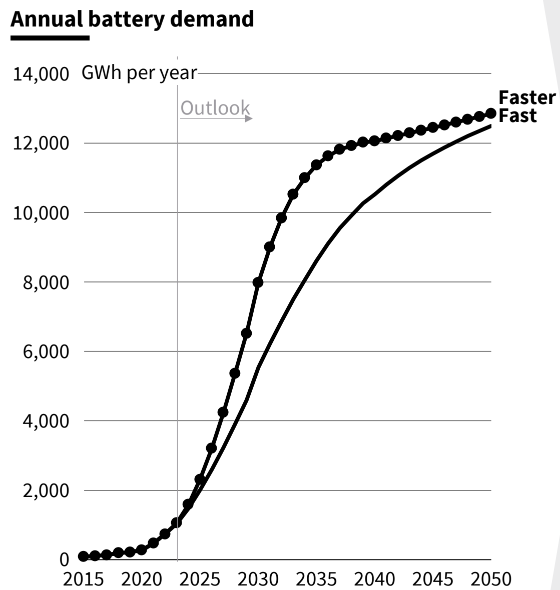
Appendix B: Modeling continued trends

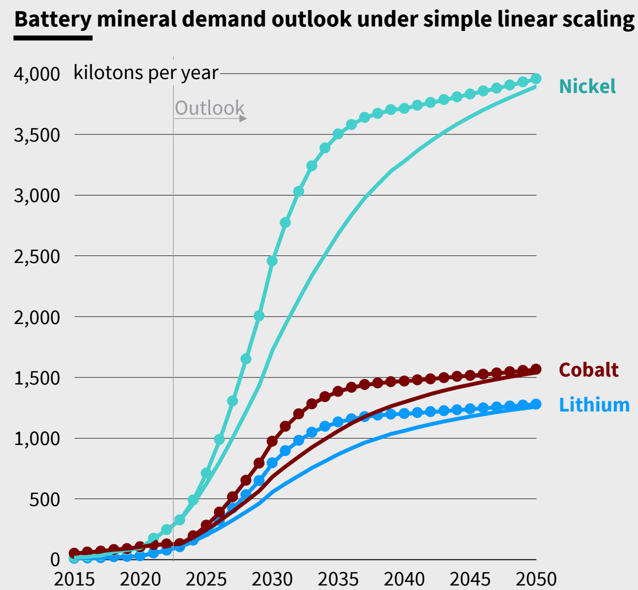
In Appendix B we walk through the three levers of the continued trends, one at a time. First, we outline a pathway that linearly scales today's mineral demand with projected battery demand. Then, we demonstrate how each solution reduces mineral demand compared to this baseline scenario.

Baseline: the simple linear scaling approach

If we linearly scale mineral demand with battery demand, it simply scales 5.5x–8x by 2030 and ~12x by 2050. This assumes we keep making batteries in exactly the same mix of chemistries, don't improve densities, don't recycle, and don't improve the efficiency of vehicles or mobility.

Exhibit 27: Battery demand and associated mineral demand under linear scaling





Source: RMI *X-Change Batteries*, RMI analysis

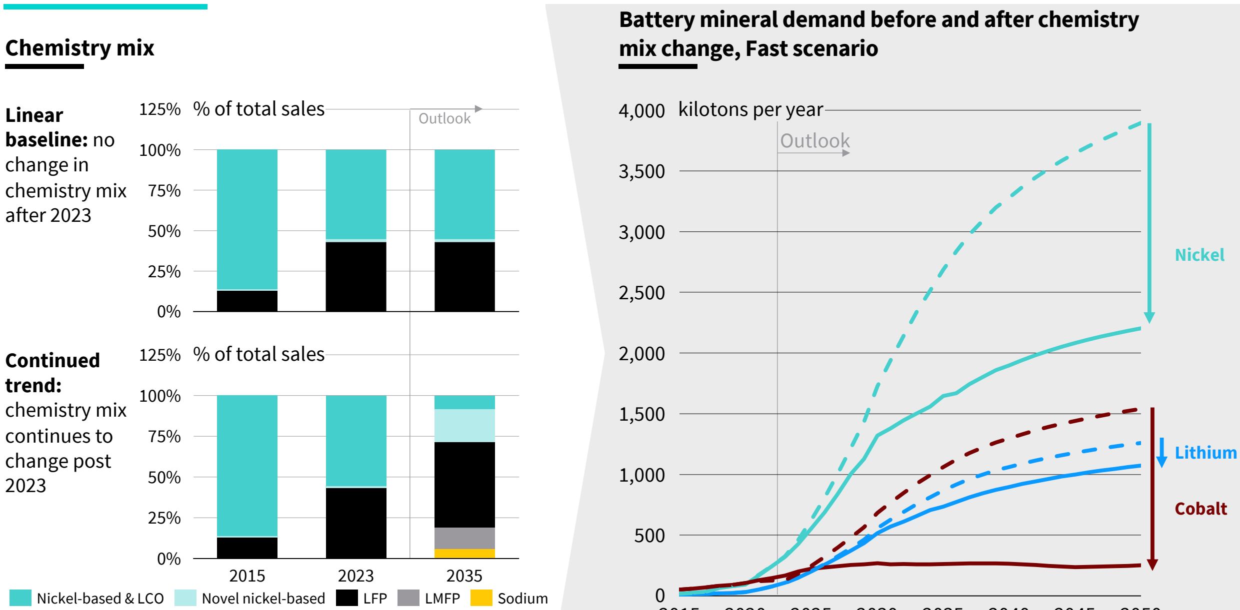
Note: This outlook only includes simply scaling up current battery mineral demand in line with battery demand. It is not representative of a realistic scenario and is purely illustrative.

The impact of continued battery chemistry changes

We use the latest BNEF chemistry mix outlook to forecast the future chemistry mix in our continued trend scenario,[88] shown on the left-hand side of Exhibit 27 in simplified groups of chemistries.

A continued shift from conventional to novel nickel, LFP, and sodium-ion batteries significantly reduces cobalt and nickel demand (while slightly reducing lithium demand) compared to the simple linear scaling baseline. Cobalt also improves because most of future demand growth comes from the transport sector, rather than consumer electronics (whose batteries use 3x–10x more cobalt per cell than the cobalt-containing batteries in some EVs).[89]

Exhibit 28: Impact of continued chemistry mix change on mineral demand



Note on groups: Nickel-based (NMC 111, NMC 532, NMC 622, NMC 811, NMC 721, NMCA, NCA85, NCA90, LMO, LNMO, LCO), Novel nickel-based (NMC 955, NMC 96Ni, LMR-NMC, NCA92, NCA95, eLNO), LFP (LFP), LMFP (LMFP), Sodium (Na-ion)

Source: BNEF *Long-Term Electric Vehicle Outlook* (2024), RMI analysis

Note: Part of the decline for cobalt comes from the sectoral redistribution of demand.

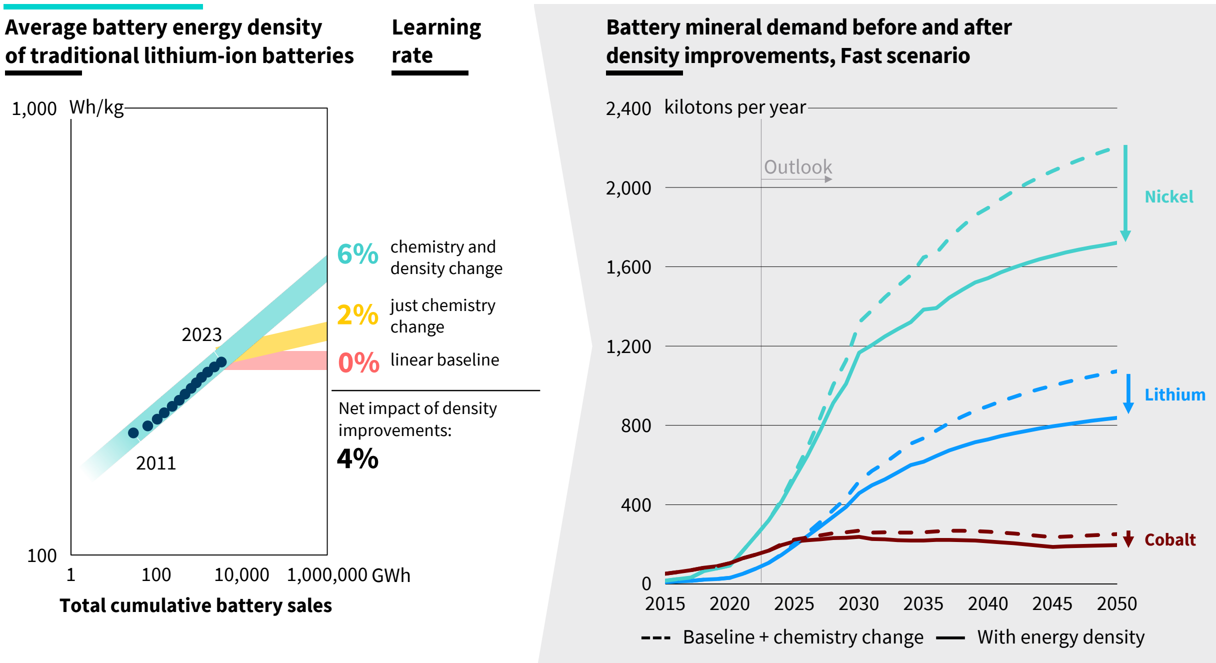
The impact of continued battery energy density improvements

In our *X-Change: Batteries* report, we analyzed the learning rate — the percentage by which energy density improved for every cumulative doubling in sales — of top-tier battery energy density, which was about 7% since 1990. In Exhibit 28 we show a similar analysis for the average energy density, based on BNEF battery data.[90]

We find that the average energy density learning rate is 6%. We estimate that one-third of this is driven by chemistry change. Hence, the learning rate from energy density improvement (for a given chemistry) is about 4%. Exhibit 28 shows the impact of assuming this learning rate, instead of 0% in the linear baseline case.

For simplicity, we assume that energy density improvements affect all minerals in the battery cell equally, resulting in the same percentage reduction for each mineral. If cell density improvements were exclusively made in the non-mineral parts of a battery, peak demand would be 10%–25% higher across our scenarios but the timing of peaks would be roughly the same. Long-term results would also be similar, if there was sufficient recycling capacity to manage the additional demand.

Exhibit 29: Impact of continued density improvements on mineral demand



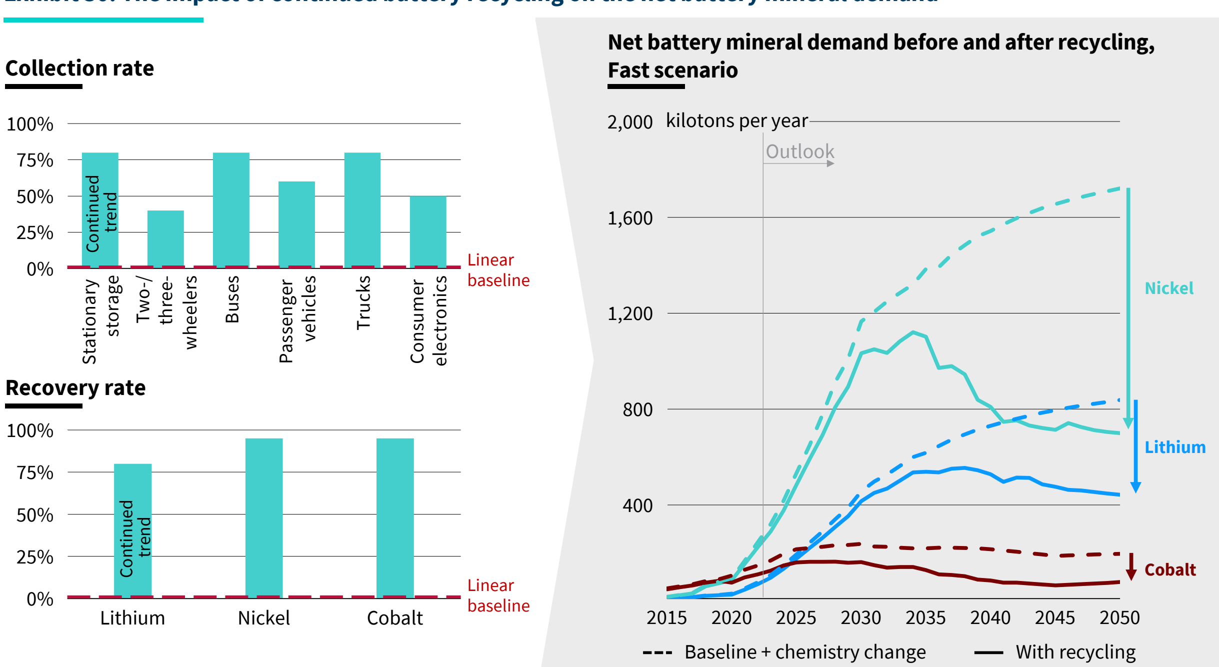
Source: BNEF *Lithium-Ion Batteries: State of the Industry* (2023), RMI analysis

The impact of continued battery recycling

Next, we layer in recycling to get to the net mineral demand — the total demand minus the recycled material. Net mineral demand is equal to the amount of minerals that will have to be mined.

After accounting for recycling, net mineral demand is projected to peak in 2038 for lithium, 2034 for nickel, and 2028 for cobalt. This is driven by batteries sold today reaching their end of life in a decade from now and getting recycled back into minerals, offsetting the demand growth from new battery sales.

Exhibit 30: The impact of continued battery recycling on the net battery mineral demand



Source: BNEF *Lithium-Ion Battery Recycling Availability Model* (2024), Gaines et al. (2023), RMI analysis

Appendix C: Modeling accelerated trends

In Appendix C we lay out the assumptions behind the accelerated trend scenario.

Faster battery chemistry mix change

To model an accelerated chemistry mix change, we follow the BNEF "aggressive sodium-ion" case,[91] which ramps to 40% of passenger EV battery sales coming from sodium-ion by 2035. While ambitious for cars, this does not include increased ambition for other sectors which could also increase their projected sodium-ion uptake (such as grid storage or two- and three-wheelers).

Faster energy density innovation

As shown in our previous report, *X-Change: Batteries*, the pace of energy density improvements of top-tier batteries is accelerating. That would suggest that the average energy density may well start rising faster as well, as the top-tier batteries of today are the average batteries of tomorrow.

In the accelerated case, we increase the learning rate from 6% (of the average) to 7% to follow the top-tier developments — keeping the average in step with the leader.[92]

Better circularity

For collection efficiencies, we ramp each sector halfway to 100% by 2030 (from current BNEF estimates) and 95% by 2040. We also ramp to today's best-in-class mineral recovery rates by 2030, including 99.6% for nickel and cobalt[93] and 95% for lithium.[94]

Finally, we ramp to improved production scrap rates and scrap collection losses that are half of current estimates by 2030, assuming that best-practice production processes with those lower rates can propagate more quickly to new markets across the globe.

Longer lifetimes

We assume a two-year increase of transport-related battery lifetimes in line with the BNEF "high lifetime" case,[95] as well as higher second-life use rates and lifetimes based on alternative assumptions from Gaines et al. (2023).[96]

Efficient vehicles

We follow the IEA (2024) "Downsized Case" and ramp to a 28% reduction in battery capacity per vehicle by 2030.[97] This is more conservative than today's state-of-the-art vehicles as well as the general values in some scenarios, such as the 42% from Riofrancos et al. (2023)[98] or the 50%–60% reduction from NRDC and EPRI.[99] As highlighted in section 3, improvement could come from a combination of vehicle efficiency as well as vehicle and battery right-sizing.

Efficient mobility

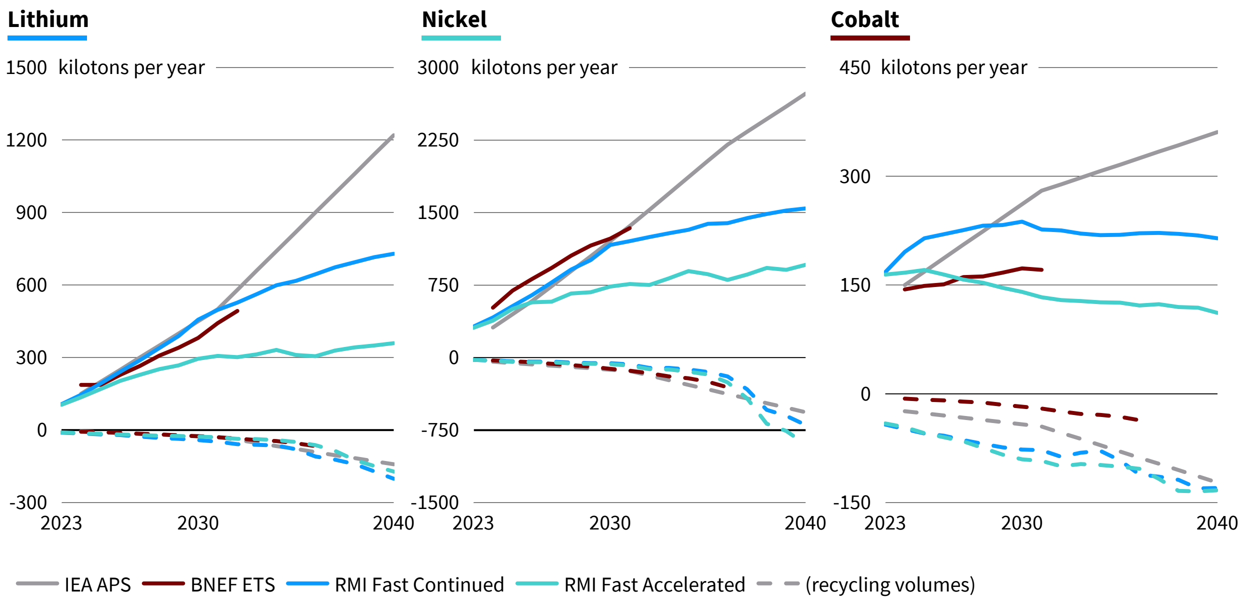
We follow the ICCT (2023) global "Avoid and Shift" scenario,[100] which linearly ramps to reductions in freight fleet demand via load factor improvements (13% by 2040 and 16% by 2050) as well as passenger demand for vehicle miles traveled (VMT) via urban planning improvements and city-specific mode shift (9% by 2030, 28% by 2040, and 37% by 2050 for the global average). We convert VMT reductions to fleet reductions by using a factor of 5/9 as in KPMG (2020).[101] These fleet reductions lower battery demand and hence mineral demand.

Appendix D: Benchmarking outlooks

Our results are comparable to other outlooks, albeit with slightly more demand reduction driven by differences in scenario assumptions. Our "Continued Trend" scenario includes battery density improvements that are absent from many other outlooks, and the IEA assumes a future chemistry mix that would require more lithium and nickel than our scenarios (we use the chemistry mix outlooks from BNEF). The RMI "Accelerated Trend" scenario reduces demand by advancing the full suite of six solutions, so demand is naturally much lower than the other scenarios. Recycling quantities are relatively similar, with most differences explained by differences in demand.

Given these outlooks' more conservative assumptions (and lack of full data beyond the 2030s), net mineral demand in the IEA and BNEF base cases only peaks for cobalt, not for nickel and lithium. Other peaks might come eventually with a longer time horizon but are delayed by lower improvements in chemistry and density compared to the RMI scenarios.

Exhibit 31: Benchmarked mineral outlooks for demand and recycling



Note: APS = Announced Pledges Scenario; ETS = Economic Transition Scenario
Source: IEA *Global Critical Minerals Outlook* (2024), BNEF *Battery Metals Supply and Demand* (2023), BNEF *Lithium-Ion Battery Recycling Availability Model* (2024), RMI analysis

Appendix E: Further context on meeting peak mining demand

As we show in section 4, meeting peak battery mining demand should be entirely feasible. In this section we provide some more details on the mineral mining outlook.

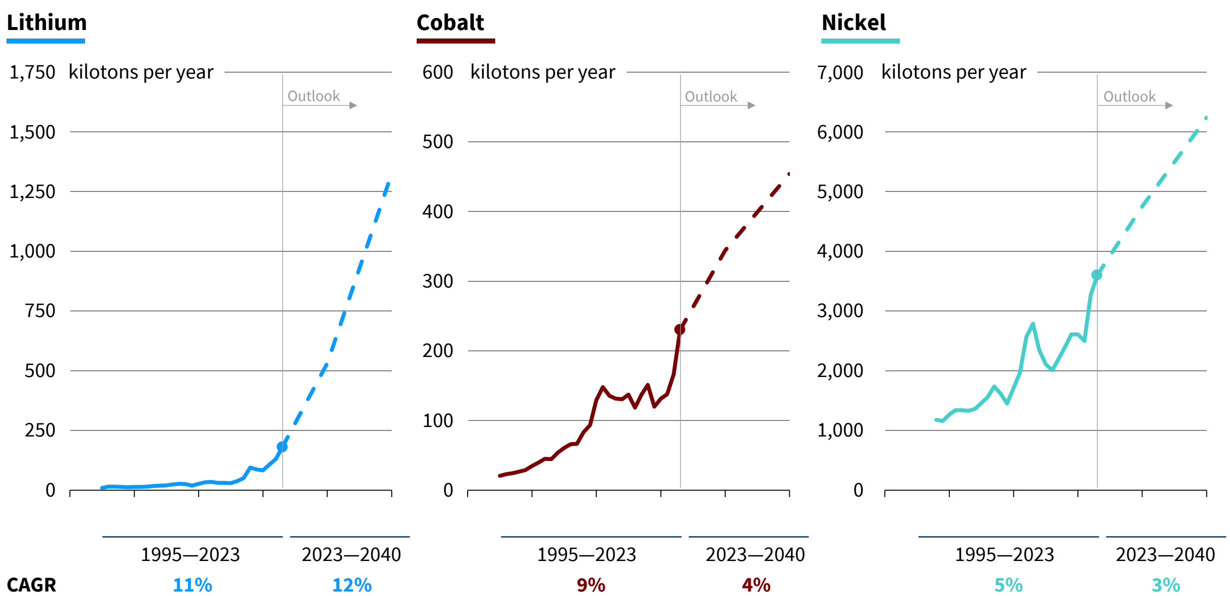
The mineral mining challenge in historical context

Without efficiency improvements or recycling, battery mineral mining would need to grow by about 12% per annum for lithium, 4% for cobalt, and 3% for nickel through 2040, according to the IEA.[102]

Such growth rates merely require a continuation of the historical growth rates. As shown in Exhibit 32, lithium, nickel, and cobalt all grew that fast — if not faster — over the past three decades than they would need to grow going forward.

We fortunately have many solutions beyond mining to meet the battery mineral demand challenge — helping to break the historical need for rapid mining expansion.

Exhibit 32: Historical mineral demand and IEA outlook



Source: USGS Lithium, Cobalt, and Nickel Commodity Summaries; IEA *Global Critical Minerals Outlook* (2024)

It is highly likely we can close the gap to the peak

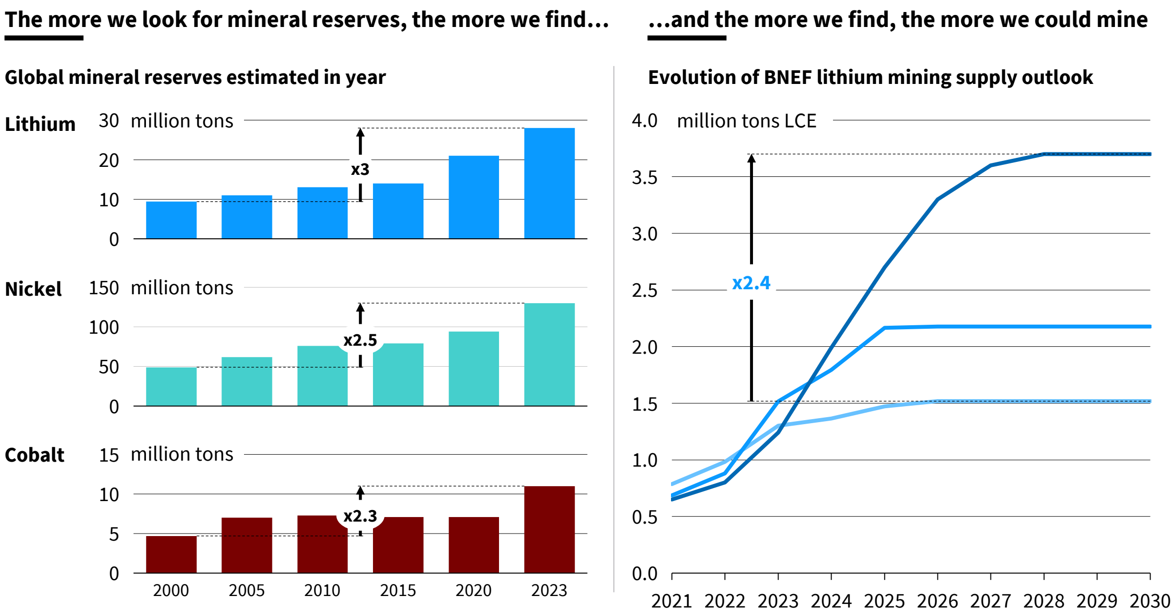
As we discuss in section 4, there is only a small gap between today's announced mining plans and peak demand. It is highly likely we can close that gap.

The harder we have looked for mineral reserves, the more we have found. For example, the US Geological Survey estimates of total global lithium reserves today are over three times higher than what they were in 2000.[103] Nickel and cobalt show a similar trend.

Analysts have been updating mining supply outlooks upward as more capacity announcements come through. As shown in Exhibit 33, the total expected mining capacity for lithium in 2030 was increased by a factor of 2.4 between the 2019 and 2023 BNEF outlooks.[104]

At that pace of annual upward corrections, within a few years we may already see 2030 projections of mineral supply exceeding peak demand in 2034–2035. And the more we reduce that peak demand through efficiency and circularity, the quicker this will happen.

Exhibit 33: Battery mineral limits keep getting updated



Source: BNEF 2019, 2021, 2023 Battery Supply and Demand Outlook; USGS Lithium, Cobalt, and Nickel Commodity Summaries; IEA *Global Critical Minerals Outlook* (2024)

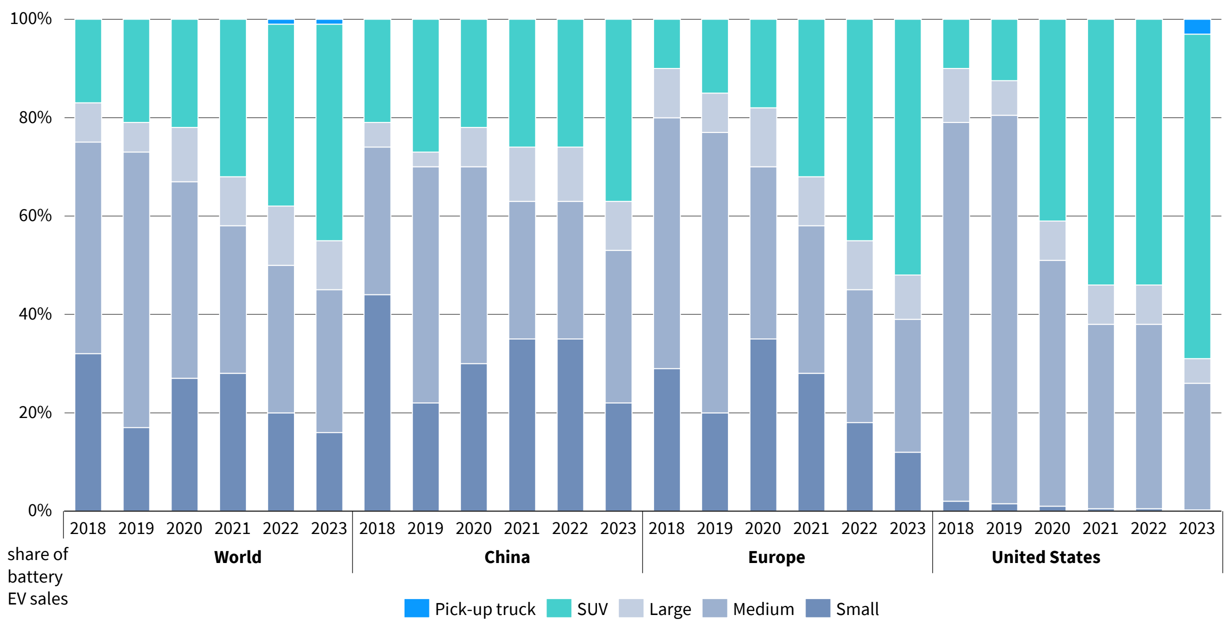
Appendix F: Further notes on the six solutions

Automotive obesity in EVs

The trend toward larger and heavier EVs is slowing efforts to reach peak mineral demand. As shown in Exhibit 34, the EV sales share of larger vehicles (such as SUVs and pick-up trucks) has been increasing from 2018 to 2023 across regions. This share has risen seven-fold in the United States and five-fold in Europe, with increases in China and elsewhere as well.

Larger vehicles require more battery capacity for a given range, which increases the demand for critical minerals such as lithium, nickel, and cobalt. This could delay peak mineral demand and circularity — but there is ample room to reverse these trends and quickly improve efficiency.

Exhibit 34: EV sales by car size, 2018–2023



Source: IEA *Global EV Outlook* (2024)

Collection rates

There is a wide divergence in battery collection rate estimates across sources. These gaps are driven by bad data availability, leading to frequent use of outdated and misinterpreted data.

The recycling rate of lithium-ion batteries is often misrepresented at a mere 5%. But recent comprehensive studies, such as those published by Circular Energy Storage as well as BNEF, suggest that the actual rate of recycling was 59% in 2019 and potentially 90% or higher today.[105] In our work we use the latest sectoral collection figures by BNEF, which range from 60% to 80% for most sectors.

These considerable discrepancies highlight the urgent need for updated and accurate data to guide both policy and public perception, ensuring that the true potential of recycling practices is both understood and achieved.

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