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Perspective

Expanding battery production enables fast technology response to mineral criticality

Björn Nykvist,[1,2,*] André Månberger,[1] Oscar Gustafsson,[1] and Lars J. Nilsson[1]
[1]Environmental and Energy Systems Studies, Lund University, Klas Anshelms väg 14, 223 63 Lund, Sweden
[2]Stockholm Environment Institute, Textilgatan 43, 120 30 Stockholm, Sweden
*Correspondence: bjorn.nykvist@miljo.lth.se
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SUMMARY

The speed at which the number of battery electric vehicles is growing is fueling debates and research on the criticality of battery materials. But rapid growth also enables fast uptake of new cathode chemistries, and electric vehicle batteries show considerable flexibility and material substitutability. Historical scaling of production is more dynamic than recognized in scenarios of future mineral scarcity, highlighting large uncertainties and calling for more analysis of a broader range of future technology pathways. Policies directed at resource security need to focus less on specific minerals and more on innovation and enhancing the diversity in technological options, materials, and supply chains.

INTRODUCTION

The rapid growth of electromobility makes the global economy increasingly dependent on battery raw materials such as lithium, cobalt, nickel, and manganese. Although gasoline and diesel are only gradually replaced, for some new materials, the rate of change is far from piecemeal. Lithium-ion (Li-ion) batteries have grown from almost no use in transport a decade ago to almost 1 TWh in personal light-duty battery electric vehicles (BEVs) in 2024, and ten times as much might be needed before the transition is complete.[1] Growing material demand has led to price surges and volatility,[2] as well as critical assessments of the feasibility of scaling value chains[3] and the urgency of more sustainable mining, refining, processing, and recycling.[4]

To evaluate how critical the material challenges are, there is a fast-growing scenario literature focusing on materials with underdeveloped supply chains, predominantly found in Li-ion battery cathodes. Since rapid scaling is needed to decarbonize transport, a key purpose of these scenarios is to analyze how quickly supply needs to grow depending on the battery technology adopted.[3,5,6] Here, we argue that the rapid historical growth in BEV sales gives rise to faster adoption of new technologies than suggested by many scenarios and that this calls for more research on how much flexibility and material substitutability there is in future supply chains, also on short- to medium-term timescales of 5–10 years.

GROWTH RATES ENABLING RAPID INNOVATION

We focus on light-duty vehicles, as these are currently the main drivers of battery material demand, and on pure BEVs, as plug-in hybrid electric vehicles account for only some 30% of electric vehicles sold and use smaller batteries. Data on BEV sales and battery volumes (in kWh) are taken from IEA Global Electric Vehicle Outlook (2019, 2022, 2025)[7–9] and IEA Global Critical Minerals Outlook (2023, 2024),[1,10] and older data from before 2017 are based on Nykvist et al.[11] Material demand is then calculated from total battery demand (in kWh), the share (in kWh) of each cathode material,[7,10–12] and using historical material intensity estimated from a range of sources, including Zeng et al.,[3] Xu et al.,[5] Kushnir et al.,[13] Bongartz et al.,[14] and Olivetti et al.[15]

Figure 1 shows the sales of BEV batteries with different Li-ion cathode chemistries over time, Figure 2A shows the market share over time, and Figure 2B shows the growth rate of each compared to last year's total (in kWh). Each new cathode technology introduced—from the early success of Tesla using nickel cobalt aluminum (NCA), through widespread use of higher nickel content nickel manganese cobalt (NMC), to the recent resurgence of lithium iron phosphate (LFP)—has grown at a striking rate when introduced, dominating growth in installed new capacity.

The growth of new chemistries is closely linked to the increase in BEV sales volumes. Ten million BEVs were sold in 2023 compared to only around ten thousand in 2010, representing a compound annual growth rate of more than 50%. Since the average size of batteries increases too, the growth rate of battery capacity during this period is higher at 65%. This means that both new technologies and incremental innovations rapidly dominate the production capacity. Comparing historical trends at different endpoints (Figure 1, insets) clearly shows that the historical technology choice does not determine the dominating technology just a few years later.

Looking at materials use shows similar, but less strong dynamics (Figure 2C). Still, for individual elements, annual growth has been very high (Figure 2D), and if the technology used in 2019 had been used in 2023, cobalt demand would have doubled and nickel would be 35% higher. Instead, phosphate (PO_4) and iron (Fe) have increased over 7-fold. Lithium is,

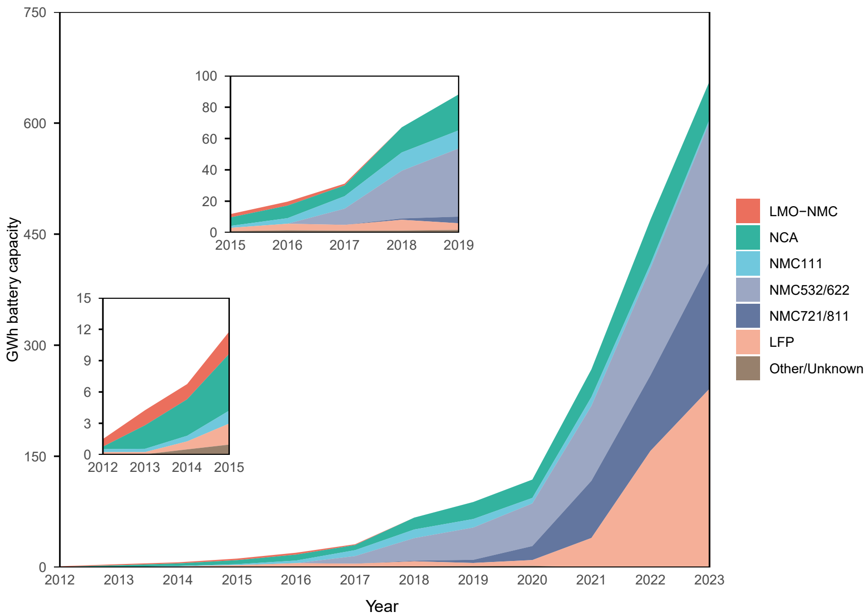

Figure 1. Historical use of different cathode chemistries

Main figure: cathode chemistries between 2012 and 2023. Inserts: development between years 2012–2015 and 2019–2023, respectively.

however, used in similar proportions across all current batteries and has similar improvements from increasing voltage and material efficiency.[16] While a more thorough analysis of this is warranted, we accounted for this trend by noting that historical material intensity in kg/kWh, on average, improves by ca 2% per year (2009–2024). Changes in chemistry choice and general improvements result in an average annual 1.8% reduction in lithium demand from 2019 to 2024 compared with the technology used in 2019.

MATERIAL COSTS AND LI-ION BATTERY DEMAND

The supply capacity of commodity markets for battery materials differs. For example, in 2022, manganese was the fifth most mined metal globally (20.0 million tons), one order of magnitude more than nickel (3.3 million tons) and roughly two orders more than cobalt (0.19 million tons) and lithium (0.13 million tons). Reviewing price data for cobalt, nickel, and lithium from investing.com and for manganese from the USGS Minerals Yearbook 2020[17] (and the same yearbooks for 2012–2019) and Mineral Commodity summaries 2024[18] (and the same summaries from 2021–2023), it is clear that smaller markets can experience higher (relative) demand growth and larger price spikes. Prices for cobalt and lithium have varied more than manganese over the last decade (see Figure 3). Comparing material price data (Figure 3) with the rapid change in cathode technology (Figures 1 and 2), batteries with lower or less volatile material prices appear to have become more successful. Cobalt-rich Li-ion chemistries that dominated in mid-2010 triggered a demand shock and a price spike for cobalt in 2018 (Figure 3A), following similar patterns in lithium prices.[2] Cobalt intensity has since declined, explained by both cobalt being replaced with nickel in NMC and the shift to LFP. Similarly, when the average nickel intensity increased, the nickel price followed, and already in 2021, intensity had begun to decline.

However, recent research shows that battery material prices are so far inelastic—meaning that fluctuating prices have not significantly influenced material demand.[19] How can we reconcile this with the faster growth of chemistries using less costly materials? A key reason is the dynamic development (Figure 1), with continued absolute growth of all BEV materials. Price increases have likely incentivized increased extraction, and as markets rapidly expanded supply, price spikes have corrected (Figure 3). The strength of the link between prices and intensity stemming from technology choices is, however, unclear. What is clear is that battery producers are involved in price hedging and trading materials over the counter, reducing exposure to spot markets,[2,20] so future research should explore the strength of this correlation and extend the analysis beyond spot market prices. In general, price increases for clean energy technologies such as batteries are historically much smaller than the price increase for the materials, as material costs have represented a small share, and efficient manufacturing processes have more than compensated for higher material costs.[20] Except for a small increase in 2022, when the recent macroeconomic uncertainty and inflation peaked, the average Li-ion battery costs have continued to decline. Historical data thus indicate that rising material prices have not slowed sales but might have influenced technology choices, driving fast-changing growth rates for individual technologies. A key question is whether this pattern will continue or if higher elasticity can be expected going forward.

First, it should be clearly recognized that the gradually slower growth in BEV sales as the transition matures will necessarily reduce how fast new technology is adopted going forward. On the other hand, research shows that the material cost share has started to dominate battery cell costs.[20] This amplifies the importance of material substitution relative to other cost-saving efforts, also at the pack level,[2] and increases the incentive to find new technologies. There are several possible candidates for the next generation of BEV batteries, including solid-state Li-ion,[2] Li-sulfur, and Li-air.[5,6] In the near term, however, sodium-ion (Na-ion)-based chemistries could have the largest impact on material use. But combining the existing cathode technologies into new blends, such as lithium manganese iron phosphate (LMFP), also creates flexibility. Although Li-ion batteries so far have better energy density, Na-ion batteries have benefits in terms of both higher charging and discharge rates as well as material availability. Performance and economics of Na-ion batteries are also approaching those of LFP.[21] Na-ion batteries could be used in some BEV

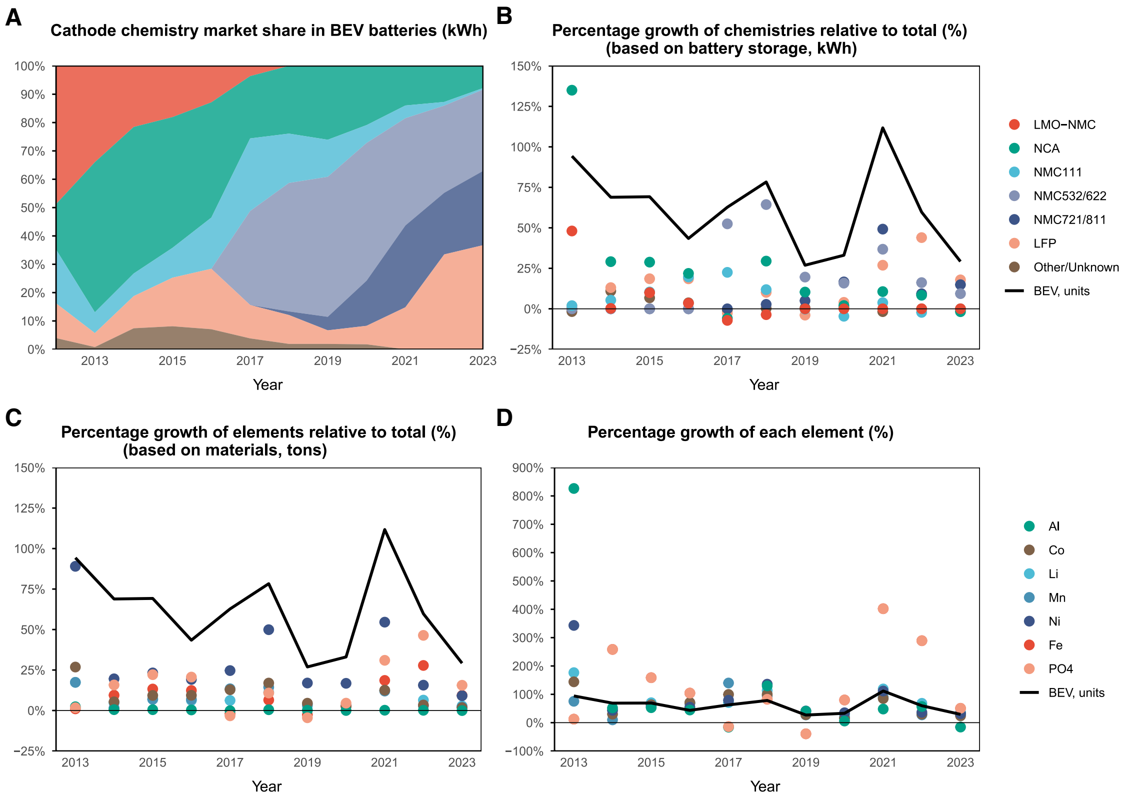

Figure 2. Share and growth of cathode chemistry and elements

(A) Cathode chemistry market share in kWh basis.
(B) Growth of each cathode chemistry compared to total last year in kWh basis.
(C) Same as (B) but for cathode materials growth compared to total last year in tons.
(D) Growth percentage of each individual element in tons (Fe under PO_4 since identical).
Black lines (B, C, and D) are growth in units of BEV.

segments and can be produced in new plants using similar manufacturing equipment used for Li-ion.[22] The outlook is uncertain, but Yao and colleagues recently showed that high lithium prices can indeed make Na-ion competitive earlier than expected,[21] suggesting continued flexibility. Overall, the rapid changes in the globally dominating battery technology indicate historical flexibility in manufacturing and suggest that new technology using other materials that offer lower cost or technical improvements can scale fast but the uncertainties are clearly large.

SCENARIOS SPANNING FUTURE UNCERTAINTY SPACE

Scenarios typically specify a given technology mix and trajectories of development to span future uncertainty. However, much lower growth rates are often assumed than what the past 15 years of BEV data show. For example, the European Union's foresight study of strategic technologies from 2023 develops two explorative scenarios, but they only differ by 11% in terms of cobalt demand by 2050.[23] Looking only 4 years back implies much higher uncertainty (Figure 1). Across scenarios by Xu et al.,[5] cobalt demand in 2050 varies by a factor of 2, but in no case is yearly growth of any material above 30%, in stark contrast to historical growth for individual materials, e.g., driven by the 300%–400% annual growth of LFP batteries in 2021 and 2022 (Figure 2D). Zeng et al.[3] explored the displacement of cobalt and used peak rates of change in battery cathode material's market shares at 5% to 10% per year; again, historical data suggest much faster change. While compound growth in scenarios can drive large changes, we argue that more research is needed to explore whether existing scenarios span the full uncertainty range.

Beyond supply-side innovations, demand across battery types and sizes is flexible due to significant heterogeneity in BEV markets. Prices of light-duty vehicles globally span an order of magnitude, from a few tens of thousands to over a hundred thousand USD. This shows significant variations in consumer willingness to pay and preferences across market segments and geographies. Heterogeneity also shows roughly 50% variation in the average size of BEV batteries across markets and varying adoption of plug-in hybrid electric vehicles vs. BEVs.[9,24] A given technology and set of preferences do not dominate all markets and segments historically, and it appears likely that several battery technologies and battery sizes will continue to co-exist in the near to mid-term.

History thus shows high substitutability between existing battery technologies, enabled by both supply-side and

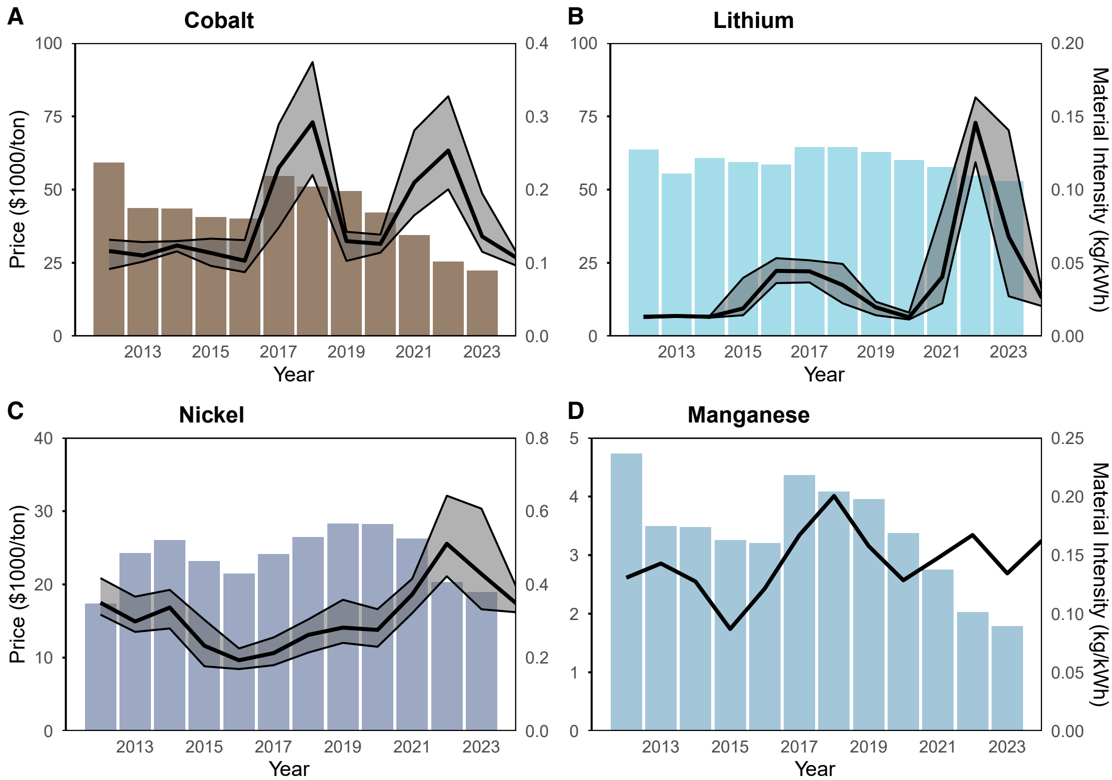

Figure 3. Material prices and intensity

Prices and material intensity for (A) cobalt, (B) lithium, (C) nickel, and (D) manganese. Bars represent the average metal material intensity across all Li-ion batteries placed on the market each year, black line is the average annual price for metal (except for lithium carbonate), and gray area represents the interannual price variability, measured as the monthly high and low.

demand-side flexibility and by the rapid growth per se. Future flexibility can stem from renewed shifts between technologies as they are incrementally improved, from new blends of cathode materials and new technologies. However, it is important to recognize that it is not a given that new innovations such as solid-state Li-ion and Na-ion—currently seeing initial commercial success—can scale in the automotive applications considered here. The flexibility and opportunity for fast innovation enabled by rapidly increasing sales must necessarily decline as markets mature. Another decade of yearly BEV growth above 50% is not realistic. Recent years show more moderate growth, and as BEVs reach a higher market share, the growth rate will fall further.

In addition, access to both existing and new technology is not certain, and sales show large regional variability, with NCA currently mainly used by Tesla vehicles sold in the US and LFP dominating in China. Regional constraints on access to technology and consumer preferences influence technology choices and the feasibility of rapid substitution. The LFP cathode is used to some extent across all vehicle segments in China, but globally, it is mainly used for the C segment (compact passenger vehicles).[24] This demand heterogeneity illustrates both the high potential for and limitations of future rapid substitution to LFP as it depends on further technical improvements or consumers outside of China accepting the performance trade-off that comes with using LFP instead of NMC. Our analysis is limited in this regard, and more granular assessments using detailed regional data on historical substitution patterns in the most important markets could yield further insights. However, it is noteworthy that for all major EV producers, the LFP chemistry both lowers material costs and reduces supply risks.[25]

While future technology choices are inherently uncertain, there is room for several additional shifts in new battery chemistries manufacturing capacity before BEVs dominate vehicle sales. Only 15% of cars sold in 2024 were BEVs, and sales and material use can increase by an order of magnitude before the transition is complete. Our argument is not that the feasibility of an individual technology enables a given opportunity for future substitutability but that both the uncertainty and opportunity are larger than often recognized and should be better accounted for in scenarios and when policy is directed toward securing the materials critical for transition.

LESSONS FOR CRITICAL MINERALS POLICY

We suggest here that current analyses and conclusions on what constitutes critical materials for batteries underestimate the high uncertainty and potential flexibility in future material demand. Emphasizing certainty in criticality based on current technologies and developing detailed regulations on specific materials as transition enablers has even been argued to lead to unintended consequences.[6,26] This includes incentivizing early recycling instead of promoting longer lifetimes and diverting attention away from research and innovation into new materials and battery chemistries with different material requirements.

While it is strategic for resource-scarce regions to increase the security of supply, focusing on expanding supply can also amplify investor speculation and price volatility.[27] Supply security is often framed as a zero-sum game that makes it difficult for rival states to collaborate: one state secures its supplies at the expense of others.[28] Instead, for most countries in the world, increasing the resilience of battery supply chains hinges more on enabling diversity in raw material supply and the actors involved and expanding the refining capacity to navigate the current phase of rapid expansion. All major BEV-producing countries have mineral import dependencies,[24,25] and the majority of the global production base and battery mineral value chain has yet to be built. Import-dependent countries or regions should also pursue policies that support research and collaborations aimed at developing batteries using fewer critical materials, in addition to collaborating on supply security. Further out, expanding stocks and recycling provide some relief by 2050. But import dependencies remain for the foreseeable future. It takes a long time before material stocks are built up and start to reduce the need for more primary extraction, and the trade of new and used vehicles further limits the supply of recycled material.[24]

The take-home message is that raw materials have always been traded, and unless a country is endowed with the necessary raw materials, electrifying transport will create new value chains and new dependencies. Countries can encourage domestic material supply, but any country aiming to produce BEVs also needs to foster research and innovation in batteries, from refining materials to battery and vehicle production, in order to raise self-sufficiency and reduce supply chain risks. Policy can both support technology development and scale production capacity and steer to avoid certain technologies with high supply risks; such interventions shape how the battery market evolves and influence mineral criticality. It is also important to remember that the new dependencies are for vehicle production, and these are less serious than the dependence on oil and liquid transport fuels in the fossil economy, where supply disruptions can have acute effects on operations.

During the past 15 years, it has been very difficult to forecast how critical a given battery technology or material will be, even in the short term. To avoid unintended consequences such as technological lock-in and the risk of spending analytical and regulatory capacity on the wrong issues, regulation should not be directed only to material security per se. Instead, policies need to be set up for a dynamic future, be more forward-looking, and focus on supporting domestic industrial innovation as well as enhancing diversity in technological options and supply chains through international collaborations.

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AUTHOR CONTRIBUTIONS

Conceptualization, B.N. and A.M.; methodology, B.N., A.M., and O.G.; data curation, B.N., A.M., and O.G.; formal analysis, B.N., A.M., and O.G.; visualization, B.N. and A.M.; writing – original draft, B.N. and A.M.; writing – review & editing, B.N., A.M., L.J.N., and O.G.; and funding acquisition, A.M., B.N., and L.J.N.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the main author used ChatGPT to improve grammar and to assist in coding of R-scripts, generating the figures. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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