Mining, Metallurgy & Exploration
https://doi.org/10.1007/s42461-024-01070-7

Challenges in the Battery Raw Materials Supply Chain: Achieving Decarbonisation from a Mineral Extraction Perspective

Landon Jackson[1] · **C. Meinke**[2] · **R. Chandramohan**[3]

Received: 25 December 2023 / Accepted: 21 August 2024

Abstract

Understanding constraints within the raw battery material supply chain is essential for making informed decisions that will ensure the battery industry's future success. The primary limiting factor for long-term mass production of batteries is mineral extraction constraints. These constraints are highlighted in a first-fill analysis which showed significant risks if lithium-ion batteries are utilised to fully support vehicle electrification and intermittent energy storage. Nickel, lithium, cobalt, and graphite reserves risk 100% depletion with significant consumption of known resources. Furthermore, over 700 new critical mineral mines will need to be developed to meet the required production rates for decarbonisation by 2050. Demand for critical minerals will out-pace mine development timelines even as improvements are made to battery energy density and compositions. Governments and the private sector need to align themselves on decarbonisation goals to establish cooperative agreements on the critical mineral supply chain by reducing the barriers to entry and increasing exploration efforts. Additional measures must also be taken to reduce the demand for critical minerals. Policy such as incentivising public transportation and biking infrastructure can be exploited to drastically reduce the mineral demand placed on the mining industry.

Keywords Raw battery materials · Supply chain · Mineral extraction · Policy · Mineral demand

1 Introduction

Over the recent years, awareness of global warming and government accords, such as the Paris Agreement, have motivated an energy transition from conventional fossil fuels to green-energy solutions. These social and environmental concerns have increased demand for alternative energy production and applications that emit lower emissions. The electrification of the transportation sector has seen an increase in spending on battery electric vehicles (BEV) by 50% between 2021 and 2022 and is expected to increase exponentially [1]. Lithium-ion batteries (LIBs) are commonly used as a source for energy storage and vehicle power due to their familiarity, relatively high energy density, long cycle life, and lack of direct greenhouse gas (GHG) emissions. The demand for vehicles LIBs is expected to increase by 33% per annum to 4700 GWh in 2030 [2]. This growth has already exceeded earlier predictions from 2018 to 2020, which only projected global demand of 2500 GWh of LIBs by 2030 [3]. This rapid transition challenges the resilience of the LIB supply chain in achieving net zero target emission (NZE) targets.

Analysts and researchers across various organisations have explored the battery supply chain in its ability to supply critical raw materials and manufacture LIB packs. One source is the International Energy Agency (IEA), which provides a yearly update on BEV and LIB market trends. The 2023 "Global EV Outlook" report outlines the diverse array of battery chemistries such as nickel-manganese-cobalt (NMC), nickel–cobalt-aluminium (NCA), and lithium-iron-phosphate (LFP). It also develops a direct correlation between metal and battery pack price. Though LFP batteries are noted as having the lowest cost, they are the most

---

✉ Landon Jackson
landon.jackson@ausenco.com;
jacksonlandon117@gmail.com

C. Meinke
connor.meinke@ausenco.com

R. Chandramohan
rajiv.chandramohan@ausenco.com

[1] EGBC, Process Consultant, Ausenco, 1050 West Pender, Suite 1200, Vancouver, BC, Canada

[2] EGBC, Senior Process Consultant, Ausenco, 401 9Th Ave, Suite 1430, Calgary, AB, Canada

[3] MAusIMM, Global Technical Director, Ausenco, 1050 West Pender, Suite 1200, Vancouver, BC, Canada

sensitive to lithium pricing due to the chemistry's heavy reliance on the metal, which may be a concern if the mining supply cannot meet demand. The report goes on to explore the demand for LIBs and the global manufacturing capacity in three different scenarios: stated government policies (STEP), announced pledges (AP), and net zero emissions (NZE) targets. The STEP and AP scenarios predict demand to be below the announced gigafactory production capacity of batteries [1]. In the NZE case, the announced battery production capacity is barely enough to meet the demand. It is important to note that these scenarios only consider battery demand for BEV and ignore energy storage needs for green energy production like solar or wind.

Xu et al. [4] expand on the IEA reports by assessing the projected global mineral demand for EV batteries until 2050. In their study, they observe two scenarios, the stated government policies (STEP) and sustainable development (SD), which implies a 30% EV sales share by 2030 according to the Paris Agreement. Following a logistic growth curve, a 25% and 50% global fleet penetration is expected by 2050, respective of the given scenarios. The study results show that mineral demand has the potential to reach and exceed a variety of mineral reserves in both scenarios. It is important to note that the authors provide a large uncertainty range in their results as they considered both BEV and plug-in hybrid electric vehicles (PHEV) when determining the mineral demand. Using PHEVs in the study lowers mineral demand but would go against SD targets derived from the Paris Agreement. The study suggests that recycling and second use of LIBs will reduce the cumulative metal demand by 20–40% in the high SD scenario given the current and projected growth. Instead, recycling should be seen as a method to maintain critical minerals within the economy and prevent the increase of demand from primary sources once the first-fill has been completed. This report also does not consider LIB storage solutions and their impact on mineral reserves and resources.

In 2021, the EU Federation for Transport & Environment commissioned an analysis of the supply and demand of battery raw materials from a European-centric perspective [5]. The scenarios used in the study follow the "European Green Deal", which expects a 54% BEV car share by 2030 with an additional 14% share to PHEV. Key factors such as growing economic demand and potential improvements in battery energy density are accounted for. The analysis shows that the demand for raw battery metal will rise steadily until 2035 unless recycling is developed. The study concludes that a circular economy within Europe can be achieved with sufficient battery recycling, and minimal critical metal addition will be needed beyond 2035. By only using the European perspective, the results are skewed, favouring local sustainability at the cost of global impact. For instance, relying solely on battery recycling requires a substantial mass of critical minerals to already be extracted from global reserves and resources. Other gaps in the analysis include impacts from electronics and storage solutions on the battery raw materials supply chain and competition for recycled battery material.

Ding et al. [6] wrote a perspective paper on the projected future status of LIB used in the automotive industry and its impact on the demand for lithium and cobalt. Using 2016 statistics, the paper assumed high and low compound annual growth rates (CAGR), 30% and 15%, respectively, to model the increase in metal demand from 2016 to 2050. Lithium and cobalt production rates were assumed to follow a high CAGR of 15% from 2016 to 2050. Even with the high production growth rate, the authors noted a significant risk of the lithium supply chain to meet demand. Cobalt supply was expected to meet demand; however, mineral reserves would be consumed. It is important to note that the paper only focused on battery demand in the automotive industry and did not include demand from other growing applications, such as storage solutions. The paper continued by delving into technology growth in LIB cathode compositions. This covered new chemistries, including the discussion of solid-state batteries and the industry's theoretical maximum energy density of NMC batteries, which is 350–400 Wh kg^{-1}. The paper highlighted the importance of improving battery chemistry to increase energy density and minimise the demand for critical metals.

Michaux [7] took a bottom-up approach using industry energy records to determine the mineral requirements to phase out fossil fuels. Various decarbonisation analyses were assessed in detail, with the most notable scenario including the electrification of 99% of the transportation sector, conversion of 85% of existing power generation to clean energy, and 2, 28, or 84 days of NZE power storage. The scenarios assessed historic battery compositions to determine the future impact on demand for critical battery minerals. Based on 2021 energy records, Michaux estimated a significant impact on copper reserves and depletion of nickel, cobalt, lithium, and graphite reserves if LIB were implemented to phase out conventional vehicles and as stationary storage. Michaux's work highlighted the importance of diversification of the green transition and the need for technological improvement to lower the energy requirements and reduce mineral demand if a total decarbonisation effort is to be achieved.

Meinke et al. [8] expanded on Michaux's work by using an energy optimiser to assess decarbonisation scenarios and provide practical strategies to meet NZE targets set by the Paris Agreement. Mineral extraction limitations from LIB implementation are retained as a significant focus of the study, incorporating up-to-date USGS 2022 reserves and resources. LIB compositions from Michaux 2021 and IEA 2022 are used to assess the impact on the supply chain. The analysis shows a significant consumption of critical mineral reserves and resources for LIB-related metals and the infeasibility of using LIB for storage solutions. Additionally, mining production would need to increase by over 20 times for certain minerals to achieve NZE targets of < 2 °C temperature rise. Solutions are provided from a Canadian and Australian perspective on opportunities to minimise mineral consumption. This includes utilising diverse technologies and updating policies to incentivise the construction and utilisation of public transportation.

This paper emphasises the battery raw material supply chain challenges from a mineral extraction perspective. Available mineral resources, constraints in production capacities, and timelines for extraction rate ramp-up to meet growing metal demand will be explored from a bottom-up approach. Technological growth in battery chemistries and energy densities will be incorporated and assessed against projected energy and material requirements in a first-fill analysis. The scenarios will be guided using the following focusing questions:

1. How many batteries will be required to support the maximum battery market penetration in the electrification of the light-duty vehicle (LDV) fleet and electrical storage capacity in 2050?
2. What is the projected impact on critical mineral reserves in 2050 using a diverse set of existing LIB compositions?
3. How will the battery raw material supply chain be affected, and what adjustments are necessary to achieve the NZE targets?

2 Timeline and Mineral Constraints

According to the IEA (2023), the surge in demand for new batteries reached 65% between the years 2021 and 2022. The growing market demand results from government initiatives and policies on consumer influence stemming from the United Nations Paris Agreement. According to the legally binding document, countries are to limit the global average temperature rise to below 2 °C to target 1.5 °C with peak emissions by 2025 and NZE by 2050 [9]. However, recent models have shown emission output growth requiring a nearly complete reduction in emissions by 2035 to achieve the 1.5 °C target [10]. The reduction plans for most countries retain 2050 NZE targets, which will set us on track for a 2 °C increase with a buffer unless emissions continue to grow. Based on the 2 °C temperature increase, the global GDP is projected to decrease by USD 5.6 trillion due to climate-related changes and worsen exponentially at higher temperature rises [11].

Achieving decarbonisation through renewable battery solutions is expected to impact the demand for critical minerals significantly. For example, the mass of critical minerals in an electric vehicle is expected to be 5 to 6 times greater than a conventional internal combustion engine (ICE) vehicle [12]. Due to the projected increase in consumption, it is important to understand the limitations of existing global reserves, resources, and production rates (Table 1). The timeline also constrains the supply of critical minerals to achieve NZE targets. Assuming mining activities start simultaneously in the year 2023 and take 10 years to achieve initial production (Fig. 1), an aggressive timeline of 17 years is left for the mining industry to supply the necessary raw materials for 2050 decarbonisation goals [8].

3 Methodology and Basis of Assessment

The methodology used to develop scenarios assessing the impact of maximum battery market penetration on mineral demand is outlined in Fig. 2. To determine critical mineral demand, energy requirements were accounted for and scaled to the year 2050 which is determined based on the number of electric vehicles required to replace internal combustion engine (ICE) vehicles and battery storage requirements for intermittent energy sources. Two days of energy storage was selected as it was the minimum amount required to securely supply energy through low solar and wind periods [15]. Total mineral demand was then calculated based on LFP, NMC, and solid-state (SSB) lithium-ion battery compositions and energy densities. Comparisons were made against global reserve, resource, and production statistics from the

Table 1 Global production, reserves, and resources of various critical minerals [13]

Global reserve stats	Current production (kt/y)	Reserves (kt)	Resources (kt)	Reserves + resources (kt)
Copper	22,000	890,000	2,960,000	3,850,000
Lithium	130	26,000	63,000	89,000
Nickel	3300	100,000	200,000	300,000
Manganese	20,100	1,700,000	11,300,000	13,000,000
Cobalt	190	8300	16,700	25,000
Graphite	1300	330,000	470,000	800,000

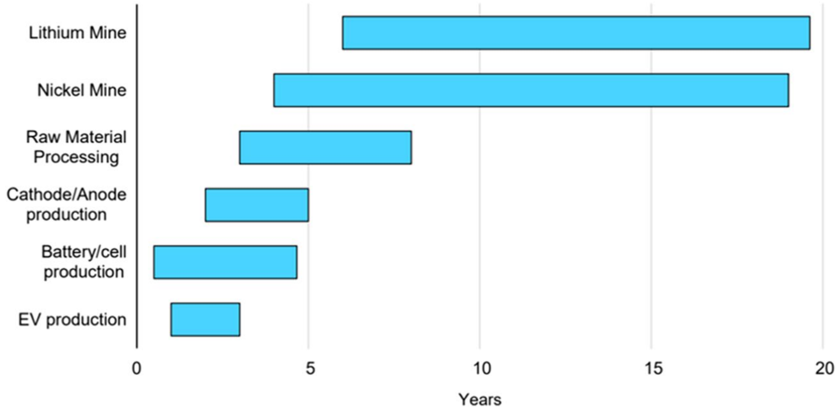

Fig. 1 Time required to commission various aspects of the battery supply chain taken from IEA "Global Supply Chains of EV Batteries" Report [14]

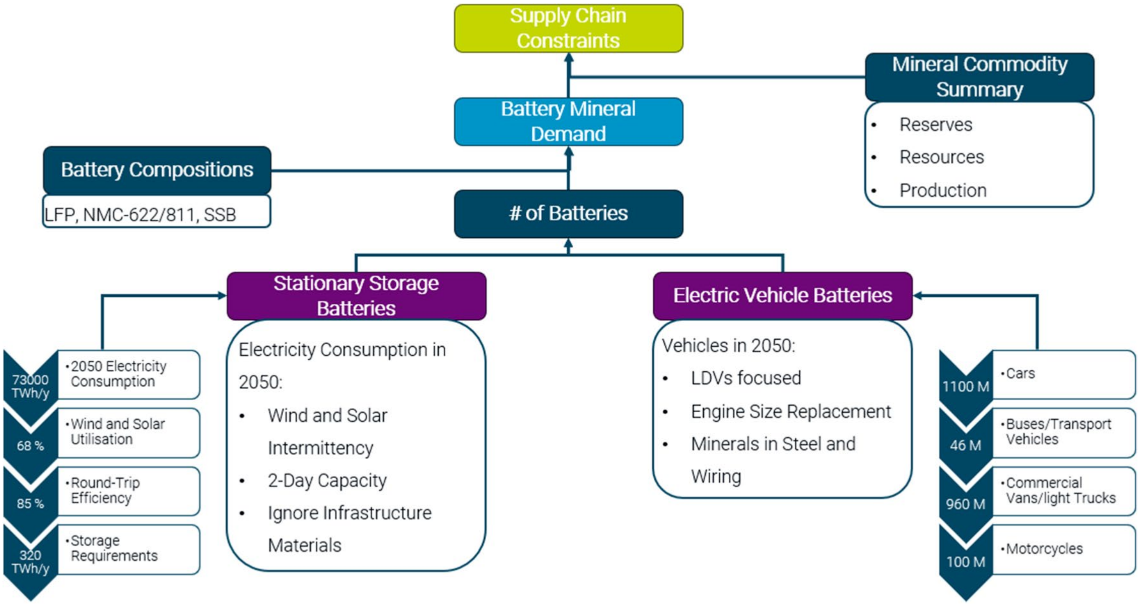

Fig. 2 Bottom-up flow diagram of methodology to determine constraints in battery raw material supply chain

US Geological Survey (USGS) database with an assumed 17-year timeline to meet first-fill demand. The feasibility of maximum battery penetration into the market was determined by taking a bottom-up approach and focused on the energy requirements for transportation and storage. Furthermore, tailored solutions were quantified and assessed to alleviate constraints in the industry's supply chain.

The basis of assessments for this paper includes:

- Fully renewable energy distribution (solar, wind, etc.) [14].
- LDV vehicle type distribution remains unchanged from 2018 to 2050 (Table 2).
- Energy growth and LDV projections taken from IEA and EIA [16, 17].
- Two days of solar and wind energy storage for intermittency risks [15].
- Final metal demand calculations based on inferred and reported battery compositions, energy density, and engine size from a variety of sources (Table 3).
- Global mining timelines require 10 years to commission with 17 years of production to reach 2050 [8].
- Does not account for metals required by energy solutions, consumer goods (i.e. smart phones), or other decarbonisation efforts.
- Recycling of used battery material achieves 100% metal recovery.
- Infrastructure materials for battery storage, such as wiring between units, are not accounted for.

The following sections will describe the relation of each input used in the assessment as well as their referencing documents.

Table 2 Projected number of vehicles by 2050 [7, 18, 19]

	Vehicles in 2018 (million)	Vehicle distribution (%)	Projected vehicles in 2050 (#)	Estimated vehicle engine size (kWh)
Passenger vehicles	690	50.1	1100	68.3
Buses and delivery trucks	29	2.1	46	227.5
Commercial vans and light trucks	600	43.3	960	153.7
Motorcycles	62	4.5	100	21.5

Table 3 Projected compositions and energy density of lithium-ion batteries by 2050 [7, 20–23]

	NMC 622	NMC 811	LFP	SSB-NMC
Projected 2050 energy density (Wh/kg)	250	360	240	500
Copper (%)	7.6%	8.1%	8.9%	8.7%
Lithium (%)	2.5%	2.1%	2.0%	2.9%
Nickel (%)	12.7%	16.7%	0.0%	17.0%
Manganese (%)	4.0%	2.1%	0.0%	2.2%
Cobalt (%)	4.3%	2.1%	0.0%	2.2%
Graphite (%)	19.8%	19.5%	22.7%	19.7%

4 Global Mineral Requirements

The two main areas of battery consumption are projected to be the transportation sector's electrification and stationary energy storage. The transportation sector is typically classified into light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs). Efforts to electrify the transportation sector have focused on replacing LDVs and their conventional internal combustion engines (ICEs) with battery electric vehicles (BEVs). Though it is technically possible for batteries to be incorporated into HDVs, the poor energy-to-weight ratio limits the economic feasibility of such an application and has been excluded from this assessment. The existing LDV fleet is reported to contain over 1.39 billion vehicles, as shown in Table 2. Statistical projections suggest this number may expand to as much as 2.21 billion by 2050 [17]. Achieving NZE would require that all existing and future LDVs be fitted with batteries, most likely utilising a form of LIB.

The second major area for battery demand is expected to stem from energy storage requirements of renewable power sources to alleviate the intermittency risk caused by wind and solar solutions. A 2-day storage was selected as the minimum number of days required to prevent supply interruptions due to the day-night and summer–winter cycles and wind intermittency [7]. Current electricity generation is reported to have reached upwards of 28,500 TWh/year, with over 60% of that relying on fossil fuels [24]. Population growth and increased electricity demand due to decarbonisation efforts could see this value double to 73,000 TWh/year in a NZE scenario [25]. A future energy distribution is provided in Fig. 3 and would require 68% of the grid (solar and wind) to be supported with energy solutions [16]. Accounting for storage and discharge losses by incorporating an efficiency factor of 84.6% [26], 321.5 TWh of storage capacity would be required to support intermittent energy supplies in 2050.

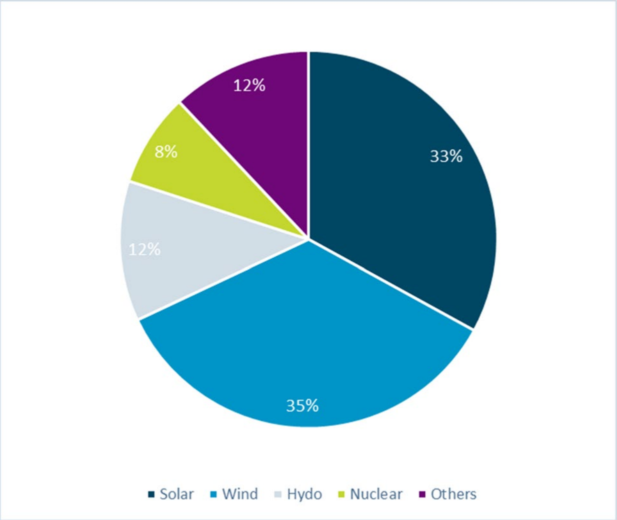

Fig. 3 Global distribution of projected NZE 2050 electricity generation [16]

The types of LIBs assessed in this study were denominated based on their cathode active material (CAM) and compositions. The battery types, energy density projections, and mineral weight distributions were inferred from various academic sources and projected beyond 2035 (Table 3). A critical mineral optimiser developed by Meinke (2023) was modified to determine the demand of battery raw materials required to achieve decarbonisation in the transportation and energy sectors. Table 4 shows the final critical mineral demand needed for vehicles and storage. An additional scenario was developed assuming that LFP battery types would be used for stationary power storage and solid-state batteries applied in vehicle electrification.

5 Assessing the Demand on the Mineral Reserves and Resources

The battery production demand for critical metals by 2050 is compared to the current global mineral reserves and resources in Table 5 and Table 6. Calculations are based on the direct metal demand to contained metal in mineral reserves and resources. Lithium, nickel, cobalt, and graphite reserves are expected to be depleted entirely depending on the chosen battery composition. Furthermore, a significant portion of the remaining mineral resources will be consumed. Such large-scale consumption will likely be matched with increasing mineral prices as lower-grade ore bodies are mined and more unfavourable bodies are extracted. This can include increased deleterious elements, more energy and reagent-intensive liberation requirements, and additional tailings production [27].

The major concern arises from the timeline to ramp up production rates. Table 7 shows the increase in current production to meet the 17-year timeline to supply the necessary critical minerals for battery production. To put into context, Table 8 is provided which shows the number of mines required to meet this target. Over 700 new mines will need to be commissioned in the next 10 years which is a significant increase compared to 2021 to 2022 which only saw 10 more active metal mines come into service [28]. Achieving a ramp-up of this magnitude will be constrained by several factors, including the ability to obtain capital for projects, the lead times on equipment, societal pushback towards large-scale mining operations, and the ability to safely operate the sites. These concepts are explored in the next section.

Only the major battery critical minerals were assessed in this study. Battery applications that include rare earths such as lanthanum and germanium would experience similar

Table 4 Total metal demand from LIB projected in 2050

Total	NMC 622	NMC 811	LFP	SSB-NMC	SSB car and LFP storage
Battery Mt	**2228**	**1547**	**2321**	**1114**	**1810**
Critical mineral Mt	**1308**	**904**	**950**	**675**	**784**
Copper	266	192	308	146	209
Lithium	60	36	50	35	42
Nickel	289	263	0	193	84
Manganese	129	60	42	44	30
Cobalt	98	34	0	25	11
Graphite	465	319	550	231	408
Other	919	643	1371	439	1026

Table 5 Projected consumption of mineral reserves based on 2050 battery demand

Reserve consumption	NMC 622	NMC 811	LFP	SSB-NMC	SSB car and LFP storage
Copper	30%	22%	35%	16%	23%
Lithium	232%	138%	193%	135%	163%
Nickel	289%	263%	-	193%	84%
Manganese	8%	4%	2%	3%	2%
Cobalt	1179%	406%	-	302%	132%
Graphite	141%	97%	167%	70%	124%

Table 6 Projected consumption of mineral reserves and resources based on 2050 battery demand

Reserve + resource consumption	NMC 622	NMC 811	LFP	SSB-NMC	SSB car and LFP storage
Copper	7%	5%	8%	4%	5%
Lithium	68%	40%	56%	40%	48%
Nickel	96%	88%	-	64%	28%
Manganese	1%	0%	0%	0%	0%
Cobalt	391%	135%	-	100%	44%
Graphite	58%	40%	69%	29%	51%

Table 7 Projected production ramp-up required to achieve mineral demand by 2050

Production increase	NMC 622	NMC 811	LFP	SSB-NMC	SSB car and LFP storage
Copper	71%	51%	82%	39%	56%
Lithium	2733%	1625%	2274%	1592%	1920%
Nickel	516%	469%	-	345%	149%
Manganese	38%	18%	12%	13%	9%
Cobalt	3029%	1042%	-	775%	340%
Graphite	2104%	1442%	2490%	1044%	1846%

Table 8 Required number of mines to match production rates for 2050 target

Mines required	Reference mine	NMC 622	NMC 811	LFP	SSB-NMC	SSB car and LFP storage
Copper	Highland Valley Copper	157	113	181	86	123
Lithium	SQM Salar del Carmen	209	124	174	122	147
Nickel	Dumont Nickel	437	397	-	292	126
Manganese	Jupiter's Tshipi Mine	3	2	1	1	1
Cobalt	Glencore's Mashamba East	576	198	-	147	65
Graphite	La Loutre Mine	288	197	341	143	253

impacts to their reserves, resources, and production capacities [15]. The results indicate that the battery raw material supply chain is at risk on the current path to decarbonisation by 2050. Understanding the limitations is essential to achieving the required mineral production capacity and meeting NZE goals.

6 The Limits to Success

Similar studies, focusing on immediate timeframes and not future growth, found significant risks to the depletion of reserves and the ability of the mining sector to ramp up production rates [7, 8, 29, 30]. This raises significant concerns about countries' ability to achieve global decarbonisation through the widespread use of battery-electric vehicles and storage solutions. The greatest limitation will come from the development of mines and the ability to ramp up production. Successful completion of mines to meet mineral demand will be limited based on:

1. The availability of material, equipment, and manpower.
2. Political will and social tensions surrounding permitting, mineral extraction, and mineral trade.
3. The ability to raise sufficient capital in a constrained timeframe.

Commissioning of mines will be constrained immediately due to the need for existing physical resources and manufacturing capacity. The strain on manufacturing supply chains will exacerbate lead times for the necessary mining and processing equipment to meet demand. Furthermore, reagents for processing materials into battery-grade chemicals for precursor cathode active material (pCAM) production will spike in price as processing and recycling plants attempt to ensure their consumable supply lines. Another challenge will be the availability of new personnel to design, commission, and operate the mines due to a decline in the mining sector graduation rates. For example, the number of US engineering graduates in the mining sector dropped by 39% between the years of 2016 and 2020 [31]. Bridging the gap between technical and practical knowledge will challenge the industry if it continues to grow. Implementing technology to increase individuals' productivity may provide some alleviation as new generations of experienced workers are brought up to speed.

The political and social realm surrounding decarbonisation and the energy transition can be a tricky paradox to navigate. Global powers want clean energy to reduce GHG emissions; however, there is a trade-off in obtaining the necessary minerals to produce renewable energy sources. This can come from increased land impact, waste production, and chemical usage. The operation of mine sites has always been a focal point for environmental protest groups, whether properly founded or in fear of the unknown. Opposition from these groups will likely mirror the increase in mining required. Depending on the political alignment and response to social unrest, government ruling can impede the development and operation of mine sites against natural economic demand. A recent example is First Quantum Minerals Ltd.'s Cobre Panama mine site's halt, which heightened copper shortage concerns in 2023 [32]. The political will of countries to ensure environmental responsibility but unimpeded operation of mines will be essential to meet critical mineral demand for batteries.

The final restriction will come from a capital perspective. Investment into mining companies can be inherently volatile due to the uncertainty of ore bodies, ability to extract minerals, and metal prices. Compound that with the insecurities in equipment supply chains, environmental pushback, and geopolitical tensions, as discussed in the previous paragraphs, and it is easy to see why investors are tentative about providing capital to mining ventures. The year of 2023 saw a 28% reduction in copper project investment even though copper is listed as a critical part of the battery raw material supply chain [33]. The lack of assurance for return on investment and exposure to risk is a significant problem that the market or government intervention must address. Investors require confidence that their investments into projects will not be lost to underlying social costs or unforeseen interruptions in service.

7 Opportunities for the Future

The projected mineral demand for batteries can quickly exceed available mining capacity. Society's ability to align itself on targets and develop new mines will need to match the mobilisation of resources, manpower, and capital similar to that of the WW2 era if 2050 decarbonisation targets are to be achieved using battery applications [34]. There are opportunities to minimise the constraints placed on the raw battery material supply chain.

The immediate solution would be to reduce the overall demand of critical minerals and avoid the use of rare earth elements. This can include the pursuit of alternative battery compositions for stationary storage solutions. Lithium-ion batteries are often favoured over other batteries due to their relative high energy density. However, in stationary applications where the weight is less important, it is more valuable to minimise overall metal demand. Using alternative batteries such as sodium-ion with aluminium collectors or iron redox flow batteries (IRFBs) may benefit both the material constraints and have lower capital expenditure as mineral prices increase. Technology growth to maximise the energy-to-weight ratio within LIBs is another aspect that can be improved. The projected energy densities cited in this study were from academic research. However, there still needs to be more certainty in what can be achieved. If battery technology development can outpace the demand for electric vehicles and storage solutions by 2050, a significant amount of mineral demand can be mitigated.

Policy is one of the largest drivers of decarbonisation, incentivising the application of renewable energy sources and the consumption of batteries. Policy will also be critical in reducing mineral demand or managing global supply chains. Regarding mineral demand, policy can be applied locally to improve transportation infrastructure through cities or promote alternative forms of transportation such as rail, electric bikes, and electric scooters. Replacing an electric car with an electric scooter would reduce mineral consumption to approximately one-hundredth of its original value [8]. Alternatively, policy can be used to improve the speed at which mines are developed. For instance, reducing the time required to obtain permits, mitigating social risks, and removing barriers to global trade. Governments must work with mining companies as venture partners or from regulation oversight. Cooperation and alignment between government and private companies may assist with streamlining the exploration and construction of critical mineral extraction projects.

Battery manufacturing companies need to focus on minimising losses in production and maximising material-to-product conversion. Battery recycling will be critical in alleviating production and end-of-life losses but provides little support in lessening the first-fill demand. Inabilities to achieve a fully circular economy will exacerbate the aforementioned supply constraints on the mineral extraction sector [35]. Furthermore, battery companies need to build closer ties with the mining sector. Ensuring a reliable upstream supply of battery-grade chemicals and materials will be critical for the uninterrupted manufacturing of battery products. In many cases, creating venture programmes between the mining and battery sectors may be beneficial to strengthen their relationships and align their interests to supply final value-added goods. The deals between Tesla and major mining companies, such as Vale and Albemarle, highlight the value in long-term mineral supply chain security [36].

The risk of missing GHG emission targets will need to be weighed against the negative impacts of rising temperatures on the planet. If society is willing to accept a change to conventional industry and lifestyles, there will be a shift to decarbonise global transportation and energy sectors. Battery technologies will be at the forefront of this movement but are challenged by their intricate supply chains. Demand on the mining sector threatens to consume existing mineral reserves, and the inability to efficiently commission mines hinders the mineral extraction production capacity. The solutions provided in this study aim to both (a) alleviate the amount of minerals consumed and (b) streamline the production ramp-up. Such goals can be achieved only through alignment and clear communication between the government, mining, and battery manufacturing sectors.

Declarations

Competing Interests The authors declare no competing interests.

References

1. International Energy Agency (2023) Global EV Outlook 2023: catching up with climate ambitions. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2023. Accessed 2 Nov 2023
2. McKinsey & Company (2022) Battery 2030: resilient, sustainable, and circular. McKinsey & Company
3. Argonne National Laboratory (2020) Lithium-ion battery supply chain for E-drive vehicles in the United States: 2010–2020. US Department of Energy, Lemont
4. Xu C, Dai Q, Gaines L et al (2020) Future material demand for automotive lithium-based batteries. Commun Mater (1);99. https://doi.org/10.1038/s43246-020-00095-x
5. Transport & Environment (2021) From dirty oil to clean batteries. European Federation for Transport and Environment AISBL, Brussels
6. Ding Y, Cano ZP, Yu A, Lu J, Chen Z (2018) Automotive Li-ion batteries: current status and future perspectives. Shanghai University, Shanghai
7. Michaux S (2021) Assessment of the extra capacity required of alternative energy electrical power systems to completely replace fossil fuels. Geol Survey of Finland
8. Meinke C, Jackson L, Erwin K Chandramohan R (2023) Assessing the feasibility of mining in achieving climate change targets using an energy optimiser. MetPlant, Adelaide
9. United Nations (2016) “The Paris Agreement,” [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement. Accessed 1 Nov 2023
10. Our World Data (2019) CO2 reduction needed to keep global temperature rise below 1.5C. [Online]. Available: https://ourworldindata.org/grapher/co2-mitigation-15c?time=2000..2100. Accessed 11 Nov 2023
11. Kompas T, Pham VH, Che TN (2018) The effects of climate change on GDP by country and the global economic gains from complying with the Paris climate accord. Earth’s Future 1153–1173. https://doi.org/10.1029/2018EF000922
12. International Energy Agency (2022a) Minerals used in clean energy technologies compared to other power generation sources. [Online]. Available: https://www.iea.org/data-and-statistics/charts/minerals-used-in-clean-energy-technologies-compared-to-other-power-generation-sources. Accessed 15 Apr 2023
13. US Geological Survey (2023) Mineral commodity summaries 2023. U.S. Department of Interior, Virginia
14. International Energy Agency (2022) Global supply chains of EV batteries. IEA, [Online]. Available: https://www.iea.org/reports/global-supply-chains-of-ev-batteries. Accessed 15 Apr 2023
15. Michaux S (2023) The Green Transition will not work as planned, what might we do instead?. [Online]. Available: https://smi.uq.edu.au/event/session/13464. Accessed 8 Dec 2023
16. International Energy Agency (2021) Net zero by 2050 - a roadmap for the global energy sector. IEA, [Online]. Available: https://www.iea.org/events/net-zero-by-2050-a-roadmap-for-the-global-energy-system. Accessed 15 Apr 2023
17. U.S. (2021) Energy Information Administration. International Energy Outlook 2021. EIA, Washington
18. M. Toll (2019) Energica’s electric motorcycles get 60% more battery for 400 km total range. electrek [Online]. Available: https://electrek.co/2019/11/05/new-2020-energica-electric-motorcycle-more-battery/. Accessed 8 Dec 2023
19. Electric Vehicle Database (2023) Useable battery capacity of fully electric vhicles. Electric Vehicle Database. [Online]. Available: https://ev-database.org/cheatsheet/useable-battery-capacity-electric-car. Accessed 8 Dec 2023
20. European Comission (2020) Critical raw materials resilience: charting a path towards greater security and sustainability. European Commision, Crussels
21. Fraunhofer ISI (2022) Solid-state battery roadmap 2035+. Fraunhofer ISI, Karlsruhe
22. Ruffo GH (2022) LFP cells are getting more energy density: 200 Wh/kg with SVolt, 230 Wh/kg with Gotion. [Online]. Available: https://www.autoevolution.com/news/lfp-cells-are-getting-more-energy-density-200-wh-kg-with-svolt-230-wh-kg-with-gotion-185117.html. Accessed 14 Nov 2023
23. Visual Capitalist – Elements (2022) The key minerals in an EV battery, MINING.COM. [Online]. Available: https://www.mining.com/web/the-key-minerals-in-an-ev-battery/. Accessed 15 Jul 2023
24. British Petroleum (2022) Statistical review of world energy. [Online]. Available: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html. Accessed 08 01 2023
25. International Energy Agency (2022) World energy outlook 2022. IEA. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2022. Accessed 20 Apr 2023
26. Massachusetts Institute of Technology (2022) The future of energy storage. MIT, Massachusetts
27. Deans G (2023) Metallurgists and modifying factors: how mets can change the world!. in *MetPlant 2023*, Adelaide
28. CDC (2022) Number of active mines by sector and year, 2021 - 2022, Centre for Disease Control. [Online]. Available: https://wwwn.cdc.gov/NIOSH-Mining/MMWC/Mine?StartYear=2021&EndYear=2022&SelectedMineType=&SelectedCommodity=. Accessed 11 Dec 2023
29. Wang S, Hausfather Z, Davis S, Lloyd J, Olson E, Liebermann L, Núñez-Mujica G, McBride J (2023) Future demand for electricity generation materials under different climate mitigation scenarios. Joule 7(2):309–332
30. Mills M (2019) The “new energy economy”: an exercise in magical thinking. Manhattan Institute
31. Abenov T, Grabbert T, Franklin-Hensler M, Larrat T (2023) Has mining lost its luster? why talent is moving elsewhere and how to bring them back. McKinsey & Company 10
32. Johnson D (2023) EXPLAINER: First Quantum, the Canadian miner at the heart of mining protests in Panama. [Online]. Available: https://www.bnnbloomberg.ca/explainer-first-quantum-the-canadian-miner-at-the-heart-of-mining-protests-in-panama-1.1998038. Accessed 9 Dec 2023
33. Els F (2023) Raising capital now biggest risk to mining companies after ESG. [Online]. Available: https://www.mining.com/raising-capital-now-biggest-risk-to-mining-companies-after-esg/. Accessed 9 Dec 2023
34. Kruszelnicki K (2023) 2000-year-old computers, limping metal gods, and fossil fuels, Adelaide, South Australia: MetPlant 2023
35. Lehmann H, Hinske C, de Margerie V, Nikolova AS (2023) The impossibilities of the circular economy. Routledge, Abingdon
36. Lambert F (2022) Tesla releases list of battery material suppliers, confirms long-term nickel deal with Vale. electrek. [Online]. Available: https://electrek.co/2022/05/06/tesla-list-battery-material-suppliers-long-term-nickel-deal-vale/. Accessed 22 Dec 2023