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ANL-24/06

Securing Critical Materials for the U.S. Electric Vehicle Industry

A Landscape Assessment of Domestic and International Supply Chains for Five Key Battery Materials

Nuclear Technologies and National Security Directorate

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Securing Critical Materials for the U.S. Electric Vehicle Industry

A Landscape Assessment of Domestic and International Supply Chains for Five Key Battery Materials

by
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EXECUTIVE SUMMARY

This study explores the prospective supply of upstream critical materials, providing insights into the U.S.'s capacity to meet its Electric Vehicle (EV) and Energy Storage System (ESS) deployment targets for 2035. It evaluates the proportion of critical materials demand that can be met by domestic upstream sources and the amount that will require non-U.S. sources.

The analysis considers geological resources and current international development activities, contributing to the understanding of mineral supply security as the global community strives for net-zero emissions by 2050. The study focuses on five materials assessed in the 2023 DOE Critical Materials Assessment – Lithium, Nickel, Cobalt, Graphite, and Manganese.

The study scrutinizes potential non-U.S. sources that could meet the United States' upstream critical material demand, examining supplies from countries with Free Trade Agreements (FTA), members of the Mineral Security Partnership (MSP), economic allies without FTAs ("Non-FTA countries"), and countries associated with Foreign Entities of Concern (FEOC) such as China and Russia. The report highlights current activities that, while not yet quantifiable, are intended to expand and secure supply chain for critical minerals among U.S. allies and partner nations.

Figure 1 summarizes a near and medium-term domestic supply and demand balance for the four analyzed materials that are designated "critical" by the 2023 DOE Critical Materials

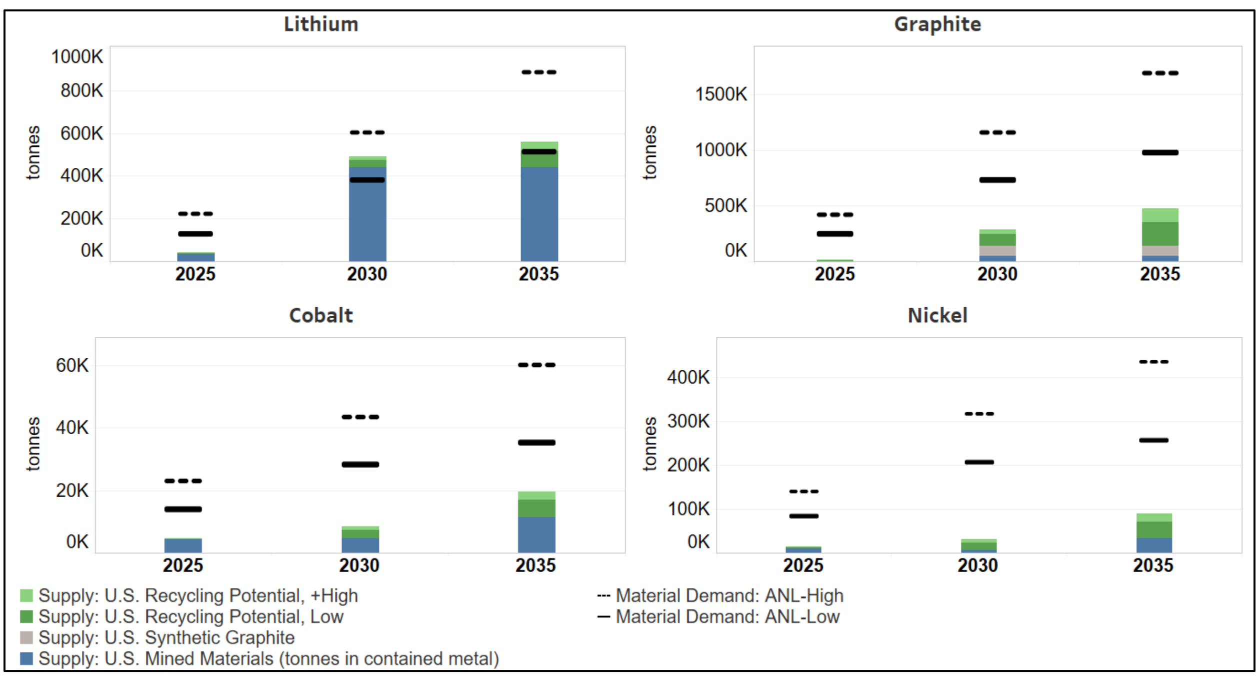

Figure 1. Anticipated upstream critical materials demand for U.S deployment that can be met by domestic sources.

Source. ANL estimates, domestic mining supply is based on data compiled from S&P Global, company reports, and new articles.
Note: Lithium is in tonnes of Lithium Carbonate Equivalent (LCE) and under graphite U.S mined materials represent natural graphite. Data last updated February 2024.

Assessment. Despite the lack of domestic mining capacity for manganese, the 2023 DOE Critical Materials Assessment deems manganese as "not critical" in both the near and medium terms, due to a lack of supply risk and its overall importance to clean energy technologies.

According to Figure 2, the U.S. appears well-positioned to meet its lithium demand through domestic production, supplemented by supply from FTA countries if needed; however, graphite sourced from economic partners in Non-FTA countries will be needed in the near and medium term. While significant capacity exists in FTA and MSP countries to support upstream cobalt and nickel demand required for U.S. deployment, the global push for decarbonization will lead to increased demand for these resources, and thus continuing ongoing U.S. government efforts to secure access to upstream materials from non-FTA trade and defense partners will be crucial to ensure supply chain security. Nickel, cobalt, and graphite represent opportunities for the U.S. to strengthen international trade relations, regional security, and clean energy deployment, as well as to expand and enhance recycling efforts, thereby ensuring a diversified and secure upstream supply.

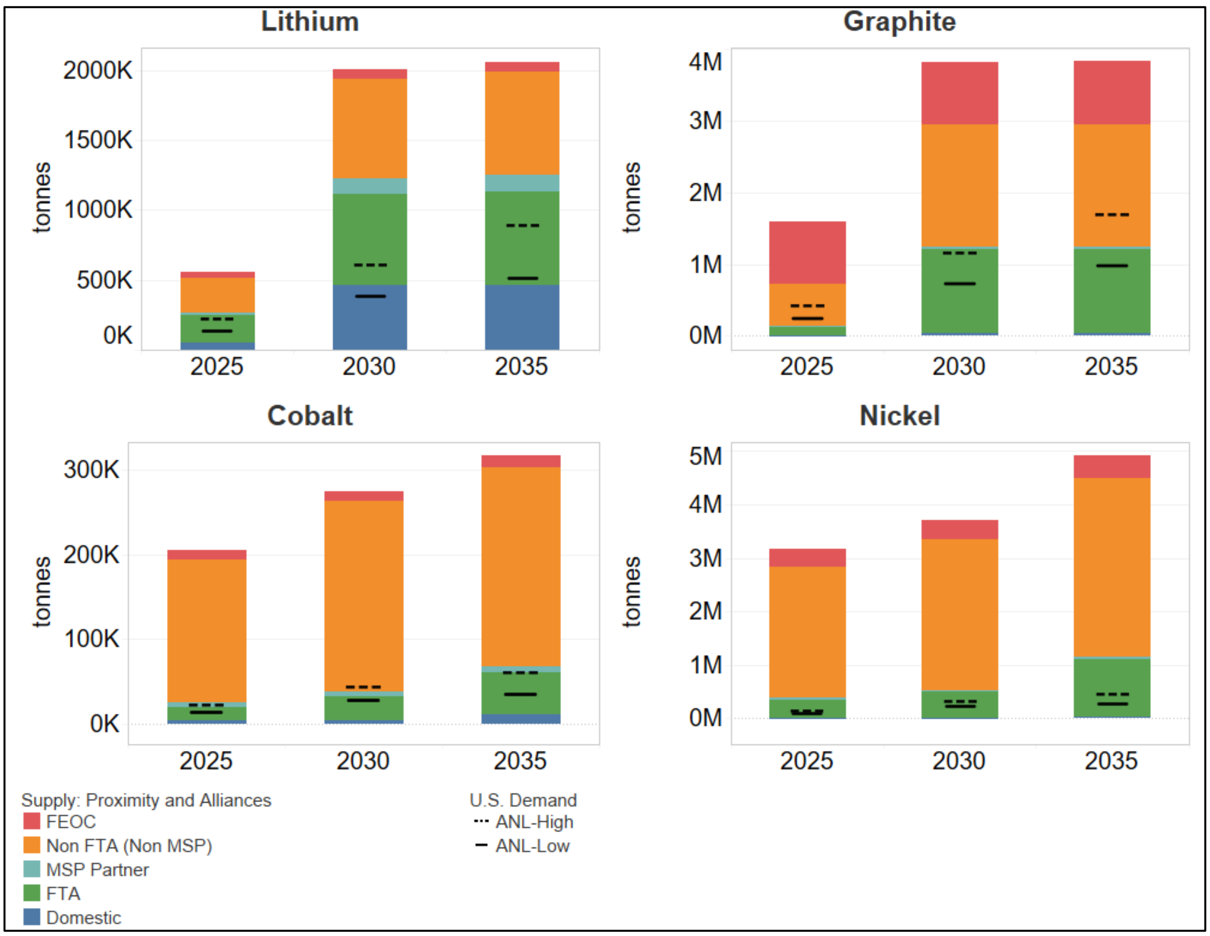

Figure 2. Potential upstream mined critical materials supply, tonnes/year, grouped by location of mines production.

Source. ANL estimates based on data compiled from USGS, S&P Global, and company reports.

Note: Lithium is in contained tonnes of lithium carbonate equivalent (LCE) while other materials are in contained tonnes of metal. Data for domestic projects last updated February 2024, for international projects September 2023.

Key highlights for the four materials are as follows:

- **Lithium:** While domestic lithium production is currently limited, the next decade could witness a surge from promising projects in the pipeline, potentially satisfying domestic demand and positioning the U.S. as a key global producer of lithium. Significant capacity exists and is planned in FTA and MSP countries, strengthening U.S. lithium security (See Figure 2).

- **Nickel:** The nickel demand needed to meet the U.S. deployment target exceeds the anticipated U.S. upstream supply for this critical material from both mining and recycling. The deficit will require supply from non-U.S. sources. FTA and MSP partners such as Australia, Canada, and Finland, have the potential to double their production in the medium term, which could strengthen access to nickel needed to meet the U.S. deployment target; however, in both the near and medium term, a significant portion of the global nickel supply may come from Non-FTA countries, particularly Indonesia, the Philippines, and a number of countries in southern Africa including Botswana and South Africa(See Figure 2).

- **Cobalt:** In the near and medium term, the supply of cobalt from U.S. mining will likely be limited, and thus recycling and non-U.S. sources will be crucial. A significant supply of mined cobalt may come from Non-FTA countries, mostly the Democratic Republic of the Congo (DRC), with most of it refined in China. To secure the cobalt supply chain, expanding processing and refining capacities offers an additional diversified trade pathway for DRC ore, along with expanded cobalt production outside of DRC, in strategic partners like Indonesia and the Philippines.

- **Graphite:** The demand for graphite exceeds the domestic supply in both the near and medium term. The current U.S. supply of natural graphite is limited, with a majority of it located in China. In the near term, meeting U.S. demand with natural graphite supply from FTA and MSP countries is unlikely. However, scaling domestic synthetic graphite production and continued innovation presents a promising potential to mitigate this risk. In the medium term, non-U.S. supply sources of natural graphite become more diverse with new planned capacity in both FTA countries like Canada and Australia and Non-FTA economic partners in Tanzania and Mozambique.

This study underscores the complexities and challenges in scaling the supply of critical materials lithium, nickel, cobalt, graphite, and manganese from both mining and recycling. These challenges span economics, technology, financing, geopolitics, environmental concerns, and human rights.

This study also proposes potential enabling approaches, and highlights current efforts underway to overcome these challenges, which could bolster U.S. efforts in securing these critical minerals. These include further expanding sustainable development and economic partnerships to increase trade with Non-FTA countries that have significant capacity; strengthening processing, refining, and recycling in the U.S. and allied nations; and fostering collaborative efforts with FTA and MSP partners to ensure the success of mining projects. Furthermore, the study includes suggestions for how mining projects can prevent conflict with local communities by ensuring that projects benefit local economies, minimize environmental impacts, and maintain strong relationships with local stakeholders. In the long term, innovation of battery chemistries that use less or no critical materials is also a key strategy.

Future analysis could expand the scope of this study to evaluate processing and refining capacity, or to examine potential shifts in trade flows based on project-level offtake agreements that have already been secured. Other areas of further study include assessing potential impacts of market reforms pursued in multilateral fora (including the emerging mineral security program among members of the International Energy Agency); evaluating MSP projects outside MSP countries' borders; incorporating sensitivities to account for uncertainties; developing supply curves for all U.S. mines to assess the economic competitiveness of the U.S. in mining critical materials; and analyzing international demand projections.

LIST OF ACRONYMS AND ABBREVIATIONS

Acronyms

ANL	Argonne National Laboratory
ARPA-E	Advanced Research Projects Agency-Energy
BatPaC	Battery Performance and Cost
BEV	battery electric vehicle
BIL	Bipartisan Infrastructure Law
BNEF	Bloomberg New Energy Finance
C5+1	Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan
CBA	Community Benefit Agreement
CFTC	Commodity Futures Trading Commission
COTECCO	Combatting Child Labor in the Democratic Republic of the Congo's Cobalt Industry
CWA	Community Workforce Agreement
DFC	Development Finance Corporation
DOD	U.S Department of Defense
DOE	U.S. Department of Energy
DOL	Department of Labor
DPA	Defense Production Act
DRC	Democratic Republic of Congo
Earth MRI	Earth Mapping Resources Initiative
ECS	Extended Continental Shelf
EGC	Entreprise Generale du Cobalt
EITI	Extractive Industries Transparency Initiative
EMIT	Earth Surface Mineral Dust Source Investigation
EOL	end-of-life
EPA	U.S. Environmental Protection Agency
ESG	environmental, social, and governance
ESS	energy storage system
EV	electric vehicle

Acronyms, cont.

EXIM	U.S. Export-Import Bank
FAST-41	Federal Improvement Permitting Steering Council
FCAB	Federal Consortium for Advanced Batteries
FEOC	Foreign Entity of Concern
FPISC	Federal Permitting Improvement Steering Council
FTA	Free Trade Agreement
GHG	greenhouse gas
GNA	Good Neighbor Agreement
HCA	Host Community Agreement
HPAL	high-pressure acid leaching
IBA	Impact Benefit Agreement
IEA	International Energy Agency
IPEF	Indo-Pacific Economic Framework for Prosperity
IPF	Intermediate Processing Facility
IRA	Inflation Reduction Act
ISA	International Seabed Authority
IWG	Interagency Working Group on Mining Laws, Regulations, and Permitting
JOGMEC	Japan Organization for Metals and Energy Security
LDV	light-duty vehicle
LED	light-emitting diode
LIBRA	Lithium-ion Battery Resources Assessment
LPO	Loan Programs Office
MHDV	medium- and heavy-duty vehicle
MINVEST	Minerals Investment Network for Vital Energy Security and Transition
MOU	Memorandum of Understanding
MSP	Mineral Security Partnership
NALS	North American Leaders’ Summit
NASA	National Aeronautics and Space Administration
NDAA	National Defense Authorization Act
NEPA	National Environmental Policy Act

Acronyms, cont.

NETL	National Energy Technology Laboratory
NHPA	National Historic Preservation Act
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
PGI	Partnership for Global Infrastructure and Investment
PLA	Project Labor Agreement
PNNL	Pacific Northwest National Laboratory
R&D	research and development
RMP	Recycled Material Producer
TIFA	Trade Investment Framework Agreement
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
USAID	U.S. Agency for International Development
USGS	U.S. Geological Survey
USMCA	U.S. Mexico Canada Agreement
USTDA	U.S. Trade and Development Agency
VTO	Vehicle Technologies Office

Abbreviations

CO	carbon monoxide
NOx	nitrogen oxide
GW	gigawatts
GWh	gigawatt-hour
kt	kiloton
kWh	kilowatt-hour
LCE	lithium carbonate equivalent
LMO	lithium manganese oxide

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I. INTRODUCTION

This study analyzes the prospective global mineral landscape, providing insights about potential pathways for the U.S. to meet its electric vehicle (EV) and energy storage system (ESS) deployment targets for 2035 in consideration of geological resources and current international development activities. These findings contribute to the understanding of mineral supply security as the U.S. and the rest of the world strive to achieve net-zero emissions by 2050. The study primarily focuses on five materials evaluated in the 2023 DOE Critical Materials Assessment[1] – Lithium, Nickel, Cobalt, Graphite, and Manganese.

The report begins by estimating the material demand necessary to meet the deployment targets, then explores potential sources for these materials from both mining and recycling. The study evaluates both domestic and international sources for these minerals, assessing the proximity of the supply chains with respect to the United States.

A considerable part of the research is devoted to examining potential supplies from countries with free trade agreements, those without, and foreign entities of concern such as China and Russia. For countries that do not have free trade agreements with the U.S, the report pinpoints current economic, sustainable development, and regional security alliances whose ongoing development serve to improve U.S. and its partners' reliable access to critical minerals. The report also underscores uncertainties and challenges in scaling mineral supply from both mining and recycling and suggests potential enabling approaches that could enhance U.S. efforts in securing critical minerals.

a. Background

As global economies race to decarbonize energy systems and combat climate change, the issue of material security is gaining prominence. Both EV and ESS are poised to play a significant role in achieving net zero emission economies. According to the U.S. Environmental Protection Agency (EPA), in the U.S., the transportation sector accounts for the largest share of greenhouse gas (GHG) emissions, contributing 28% of GHG as of 2021.[2] This was closely followed by electricity production, which was responsible for 25% of GHG emissions in the same year (U.S. EPA, n.d.). Mobile sources, which include highway vehicles and non-road mobile sources such as aircraft and locomotives, together are responsible for the majority of carbon monoxide (CO) and nitrogen oxide (NOx) emissions nationwide.[3] The U.S. government has identified that the electrification of transportation and the decarbonization of electric grid are crucial steps towards meeting net-zero goals, reducing air pollution, and reducing dependence on fossil fuels that are subject to volatile global markets. This transition represents a pivotal shift towards a more sustainable and resilient energy future.

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[1] https://www.energy.gov/sites/default/files/2023-07/doe-critical-material-assessment_07312023.pdf

[2] https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

[3] https://gispub.epa.gov/air/trendsreport/2022/#sources

Global deployment targets

Countries worldwide have implemented robust policies to accelerate the deployment of EVs and grid-scale ESS. Based on announced government targets that go beyond existing policies, global EV sales are projected to rise to 45 million by 2030, accounting for approximately 35% of all vehicle sales. The major global markets for EVs are China, Europe, and the U.S. (IEA, 2023a). Furthermore, according to the International Energy Agency (IEA), grid-scale capacity is expected to increase at an average rate of 120 gigawatts (GW) per year from 2023 to 2030, with an anticipated addition of about 170 GW capacity in 2030. China and the U.S. are leading these deployment targets as well (IEA, 2023b).

The U.S. has established objectives to deploy both electric transportation and grid storage, significantly bolstered by the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA). For example, the U.S. government aims for EVs to constitute 50% of all new vehicle sales by 2030 (The White House, 2023). It is also projected that the BIL and IRA will result in a cumulative installed capacity of battery storage ranging from 50 to 100 GW by 2030, boosting wind and solar power generation to around 80% of electricity generation (Steinberg et al., 2023).

Amidst these ongoing U.S. efforts to strengthen battery supply chains domestically and among trade partners and allies as detailed in Section II, questions persist regarding the reliability of critical material supplies needed to achieve U.S. targets, including:[4]

i. Whether there are sufficient materials for battery production to meet U.S. and global deployment targets for EV and ESS.

ii. Whether the U.S. can diversify its battery supply chains substantially reduce energy security risks posed by foreign entities of concern.

Industrial policy drivers

Numerous strategies are being employed to diversify, secure, and strengthen supply chains to support these deployment targets (U.S. DOE, 2022; IEA, 2022; European Commission, 2023). These include policy tools such as tax credits, subsidies, grants, local content requirements, and international partnerships, with the objective of expanding domestic capacities, diversifying sources, and improving supply chain transparency.

For example, the U.S.'s IRA, an industrial policy estimated to provide $369 billion in tax credits and other funding mechanisms across sectors, provides substantial support for EV and ES (Congressional Research Service, 2022). The IRA includes an investment tax credit, Advanced Energy Credit (Internal Revenue Code 48C), that subsidizes up to 30% of the investment cost in establishing processing, refining, recycling, and manufacturing facilities, including those for battery materials, in the U.S. as informed by the DOE's 2023 Critical Materials Assessment described below. The IRA also includes an Advanced Manufacturing Production Tax Credit (Internal Revenue Code 45X) which supports the production of batteries in the U.S., including the manufacture of critical minerals and production of electrode active materials, cells, and modules.

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[4] https://www.csis.org/analysis/why-new-climate-bill-also-about-competition-china

Growth in domestic manufacturing as a result of 48C and 45X will serve as a demand signal for raw materials, such as mined ore and manufacturing scrap, and secondary materials. Functioning as a direct demand pull, the IRA includes a Clean Vehicle Credit (30D) worth up to $7,500 toward the purchase of a new EV (Internal Revenue Service, n.d.) for personal (i.e., non-commercial) use, with certain price, income, final assembly, and battery sourcing requirements. To drive supply chain diversification, qualifying for half ($3,750) of the 30D credit requires that an increasing share of the value of the critical minerals contained in EV batteries be extracted or processed in the U.S. or a country with which the U.S. has a Free Trade Agreement (FTA), or be recycled in North America. This critical mineral value percentage increases from 40% in 2023 to 80% in 2027 and later. Qualifying for the other $3,750 requires that an increasing share of the value of the battery components contained in EV batteries be manufactured or assembled in the U.S., Canada, or Mexico. This battery component value percentage increases from 50% in 2023 to 100% in 2029 and later (Congressional Research Service, 2022). Starting in 2024, electric vehicles in the U.S. are prohibited from using battery components that were manufactured or assembled by Foreign Entities of Concern (FEOC) to be eligible for the 30D tax credit. Starting in 2025, there will be a prohibition on the use of critical minerals that were extracted, processed, or recycled by FEOC for vehicles qualifying for the credit.[5] The IRA's incentives are already driving automakers to assess their supply chains and seek offtake agreements that align with the requirements for the tax credit.[6]

A February 2024 report by Bloomberg New Energy Finance (BNEF) ranked 30 countries on their "potential to build a secure, reliable, and sustainable lithium-ion battery supply chain.[7] BNEF ranked Canada first, China second, and the U.S. third, and designated Mexico as the report's most improved, rising 8 spots since 2023. BNEF described the North American region as "excelling" in their battery supply chain efforts, crediting the region's success to "clear policy commitment and implementation." BNEF estimates there has been $87 billion of investment made in the battery supply chain in the U.S. since the passage of the IRA.

Leveraging previous works

This literature review focuses on several notable studies that have investigated concerns surrounding material availability.

Initiated by President Biden's Executive Order 14017, the 100-Day Supply Chain Review report offers a comprehensive analysis of the vulnerabilities and opportunities in the supply chains of key products, including advanced batteries.[8] The report underscores China's dominance in the high-capacity battery supply chain, with over 75% of global cell fabrication capacity. This dominance is attributed to government investment in raw material processing, component and cell manufacturing, and electric-vehicle deployment support. The study significantly contributes to the

5 https://www.federalregister.gov/documents/2023/12/04/2023-26513/section-30d-excluded-entities

6 https://www.energypolicy.columbia.edu/publications/the-ira-and-the-us-battery-supply-chain-one-year-on/

7 https://about.bnef.com/blog/china-drops-to-second-in-bloombergnefs-global-lithium-ion-battery-supply-chain-ranking-as-canada-comes-out-on-top/

8 http://www.whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf

discourse on battery material availability and the strategic importance of securing supply chains for batteries in the U.S.

The Department of Energy's Energy Storage Supply Chain Report provides an overview of the supply chain resilience associated with several grid energy storage technologies.[9] This study emphasizes the importance of understanding and addressing supply chain risks to ensure the sustainability and resilience of grid storage technologies. The study analyzes the vulnerabilities of each supply chain from the production of battery materials to the production of batteries and other storage systems, thereby informing strategic policy decisions.

The 2023 Critical Materials Assessment by the Department of Energy evaluates materials for their criticality to global clean energy technology supply chains.[10] The report provides an overview of market developments since the 2019 report, focusing on sectors such as electric vehicles, energy storage, hydrogen, light-emitting diode (LED) lighting, solar energy, and power electronics. It identifies a list of energy-specific critical and near-critical materials through 2035, including lithium, nickel, cobalt, and natural graphite. These materials are integral to clean energy technologies and have a high risk of supply disruption.

A 2023 study by Donson et al., conducted at DOE's Lawrence Berkeley National Laboratory, suggests total resources in the Salton Sea region could contain over 3,400 kilotons (kt) of lithium (equivalent to 18,098 kt of lithium carbonate equivalent (LCE)). This amount is sufficient to support more than 375 million EV batteries, which exceeds the number of vehicles currently on U.S. roads.[11]

A 2023 study by S&P Global Market Intelligence assessed the impact of the IRA on the North American metals and mineral market.[12] The study found that the IRA could drive U.S. demand for lithium, cobalt, and nickel, with demand projected to increase 23-fold by 2035 compared to 2021 levels. The study also identified recycling as a potential solution to reduce net demand for these materials, albeit in the longer term, given the nascent state of the U.S. battery recycling industry, the long lifespan of EV batteries, and the potential for second-life applications for EV batteries. The study also highlighted potential competition from other countries for resources outside the U.S., with IRA geographical and value sourcing requirements and restrictions for FEOC potentially exacerbating the U.S.'s ability to secure supplies from abroad. The study further suggests that lithium, nickel, and cobalt minerals are unlikely to meet certain IRA sourcing requirements. However, this conclusion does not take into account that certain value requirements and sourcing restrictions apply only to critical minerals and battery components used in EVs seeking to qualify for the 30D tax credit. The 30D tax credit is subject to limits on sales price and the buyer's income and is only available for EVs weighing less than 14,000 pounds intended for non-commercial use that are assembled in North America. Automakers may alternatively source equipment more broadly for leased EVs and any EVs intended for commercial use and receive a tax credit valued at the incremental purchase price of the EV versus to an internal combustion

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9 https://www.energy.gov/sites/default/files/2022-02/Energy%20Storage%20Supply%20Chain%20Report%20-%20final.pdf

10 https://www.energy.gov/sites/default/files/2023-05/2023-critical-materials-assessment.pdf

11 https://newscenter.lbl.gov/2023/12/12/berkeley-lab-led-analysis-salton-sea-region-domestic-lithium-resource/

12 https://cdn.ihsmarkit.com/www/prot/pdf/0823/Impact-IRA-Metals-Minerals-Report-FINAL-August2023.pdf

engine vehicle with comparable size and use. The requirements for qualifying for the 30D tax credit are especially stringent, while other EV purchase incentives do not require such rigorous due diligence on sourcing. Acknowledging the complexity of global supply chains for minerals, manufacturers have a number of options available to them to diversify and secure the global supply chain for minerals.

The white paper titled "Energizing American Battery Storage Manufacturing" by the Solar Energy Industry Association offers a review of the energy storage industry's projected landscape in the U.S and FTA countries by 2030.[13] It pinpoints potential bottlenecks in the battery supply chain, including access to raw and processed materials. The paper conducts an in-depth review of three key materials: lithium, phosphorus, and graphite. It highlights the potential competition for these resources with overseas battery manufacturers. The paper suggests that a substantial amount of lithium sourced from FTA countries is likely to be exported to China. The paper also identifies graphite as a potential chokepoint, which could impact the U.S battery industry significantly.

Lastly, a 2023 study by de la Chesnaye et al. at OnLocation, found that the demand for lithium, nickel, cobalt, and manganese, which are essential for EVs to meet net-zero targets, will significantly increase. By 2050, compared to 2022 levels, the demand for lithium is projected to surge by almost 18 times, nickel by just over 25 times, cobalt by more than 15 times, and manganese by more than 15 times. However, the OnLocation study does not provide an analysis of the potential supply needed to meet this projected demand. Instead, it focuses on estimating demand and highlighting the challenges in sourcing these critical materials for EVs.

This study builds upon existing research and leverages the most up-to-date data from a variety of sources, including S&P Global, peer-reviewed journal articles, mining company websites and reports, and the U.S. Geological Survey (USGS). It provides an in-depth analysis of the projected demand for five critical materials: lithium, nickel, cobalt, graphite, and manganese, necessary for both EV and ES. The study also examines the prospective landscape of domestic and global raw materials production, estimating the quantity of these materials that could potentially be processed into battery grade materials. Additionally, it explores the potential of recycling end-of-life (EOL) EVs and battery manufacturing scrap to fulfill the anticipated demand in the U.S. The study sheds light on the economic and international trade issues that underpin material availability, investigates the feasibility and alternatives, and describes current measures underway to support the U.S.' achieving its EV and ES deployment goals in the medium term.

This study acknowledges the uncertainties and limitations inherent in the analysis provided. For example, while the study estimates the supply of raw materials that could potentially be processed into battery-grade materials, it does not evaluate where this processing might take place, as the assessment of processing and refinery was not within the scope of this study. The study operates under the assumption that there is a strong global desire among countries to add value to resources where resources are produced. However, it also recognizes that early starters in processing and refinery activities such as China, may have a significant influence on the processing

13 https://www.seia.org/sites/default/files/2023-11/EMBARGOED-Final%20Energy%20Storage%20Roadmap-Nov%202023.pdf

of raw materials, at least in the near term. This highlights the dynamic and complex nature of the global supply chain for these critical materials.

b. Critical Materials Overview

Critical materials, specifically Lithium, Nickel, Cobalt, Graphite, and Manganese[14], play an essential role in the manufacturing of batteries that power EVs and ES systems, as well as consumer products such as cell phones and laptops. Additionally, these minerals are also used in the chemicals and metallurgy sectors. Given their finite nature and geographical distribution, it is imperative to ensure that the U.S. has access to these materials as global economies progress towards achieving their net-zero and energy security goals. This subsection offers a brief overview of these critical minerals, elucidating their role in EV and ES, their global distribution, and recycling potential.

Anticipated increase in minerals demand

Global targets for EVs and ES will increase demand for critical minerals. Under the IEA's net-zero scenario, the global demand for these minerals is projected to more than double from the near term (2025) to the medium term (2030).

The need for EV materials is the primary force driving the demand for battery materials, compared with ES (See Figure 3). Argonne National Laboratory (ANL) projects a substantial surge in mineral demand to meet U.S. deployment targets on the trajectory to achieving net-zero emissions (See Figure 3, and see Appendix I: Demand Projections Methodology). ANL estimates that the ES technologies to be deployed will predominantly use lithium and graphite, in addition to other non-critical materials. Meanwhile, cobalt, manganese, and nickel are expected to maintain their prominence in EVs.

Both IEA and ANL estimate that lithium-ion battery technologies are likely to remain intensive in graphite, lithium, and nickel in the near and medium term, underscoring the need to scale and secure the supply chain of these materials(See Figure 4).

14 The 2023 DOE Critical Materials Assessment deems manganese as "not critical" in both the near and medium terms, due to a lack of supply risk and its overall importance to clean energy technologies. USGS designates manganese as a critical mineral in its 2022 list of critical minerals. U.S. Geological Survey Releases 2022 List of Critical Minerals | U.S. Geological Survey (usgs.gov)

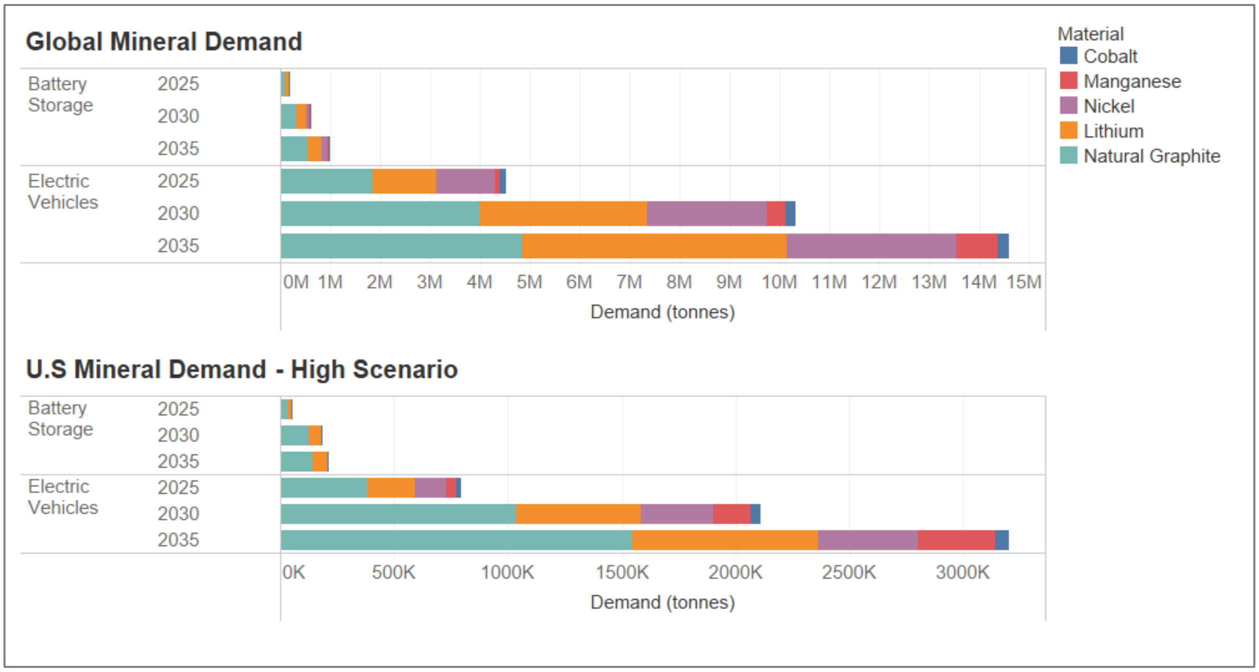

Figure 3. Mineral demand.
Source. Global mineral demand data is from IEA, 2023c and U.S. demand estimated by Argonne National Lab (ANL).
Note: IEA global mineral demand for ES is based on Net Zero scenario base case, while global EV demand is based on Net Zero scenario but wider use of silicon anode. ANL assumptions for U.S. demand are discussed in Section III.

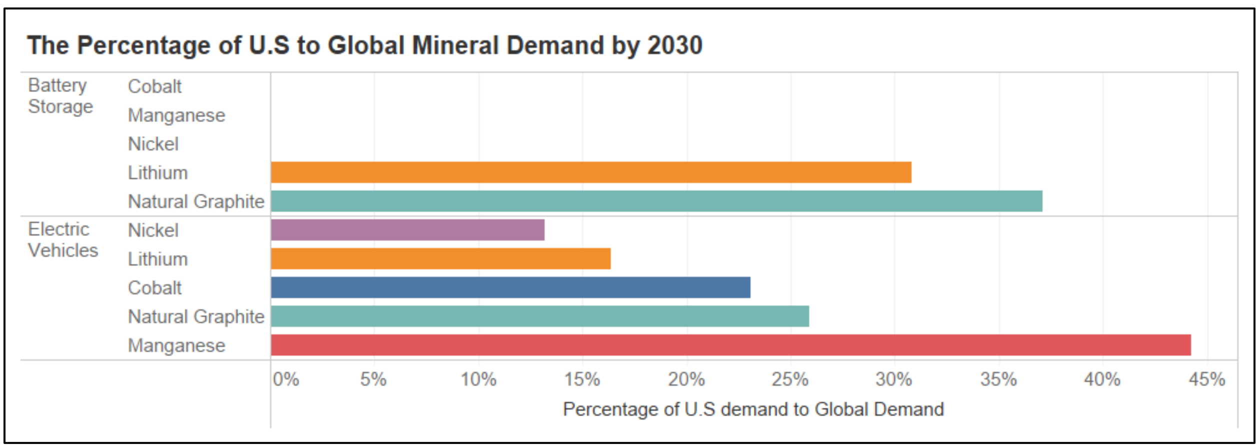

Figure 4. U.S. to global mineral demand ratio.
Source. ANL estimates, Global Mineral Demand data is from IEA, 2023c.

Geographical distribution of critical minerals

Understanding the global distribution of critical minerals is crucial for decision-makers to clarify the dynamics of trade and geopolitical relationships. Figure 5 and Figure 6 illustrate the geographical distribution of mining of the five materials under evaluation in 2022 and 2030, respectively. In 2022 about 39 countries are involved in the extraction of minerals. By 2030, extraction is planned in over 61 countries, with notable expansions of extraction capacity in Africa, Europe, and South America.

Figure 5. Distribution of mining production of key critical minerals in 2022.
Source: Data from USGS, 2023.

Figure 6. Anticipated distribution of mining production of key critical minerals in 2030.
Source: ANL estimates based on data compiled from USGS, S&P Global, and company reports.
Note: Data for domestic projects last updated February 2024, for international projects September 2023.

Figure 7 highlights the leading producers of Lithium, Nickel, Natural Graphite, and Cobalt. A substantial portion of the world's Lithium is currently mined in Australia, Chile, and China. Significant Nickel production occurs in Indonesia, the Philippines, Russia, and New Caledonia. China, Mozambique, and Madagascar are major contributors to the global extraction of Natural

Graphite. Lastly, the Democratic Republic of Congo (DRC), Indonesia, and Russia are key players in the production of Cobalt.

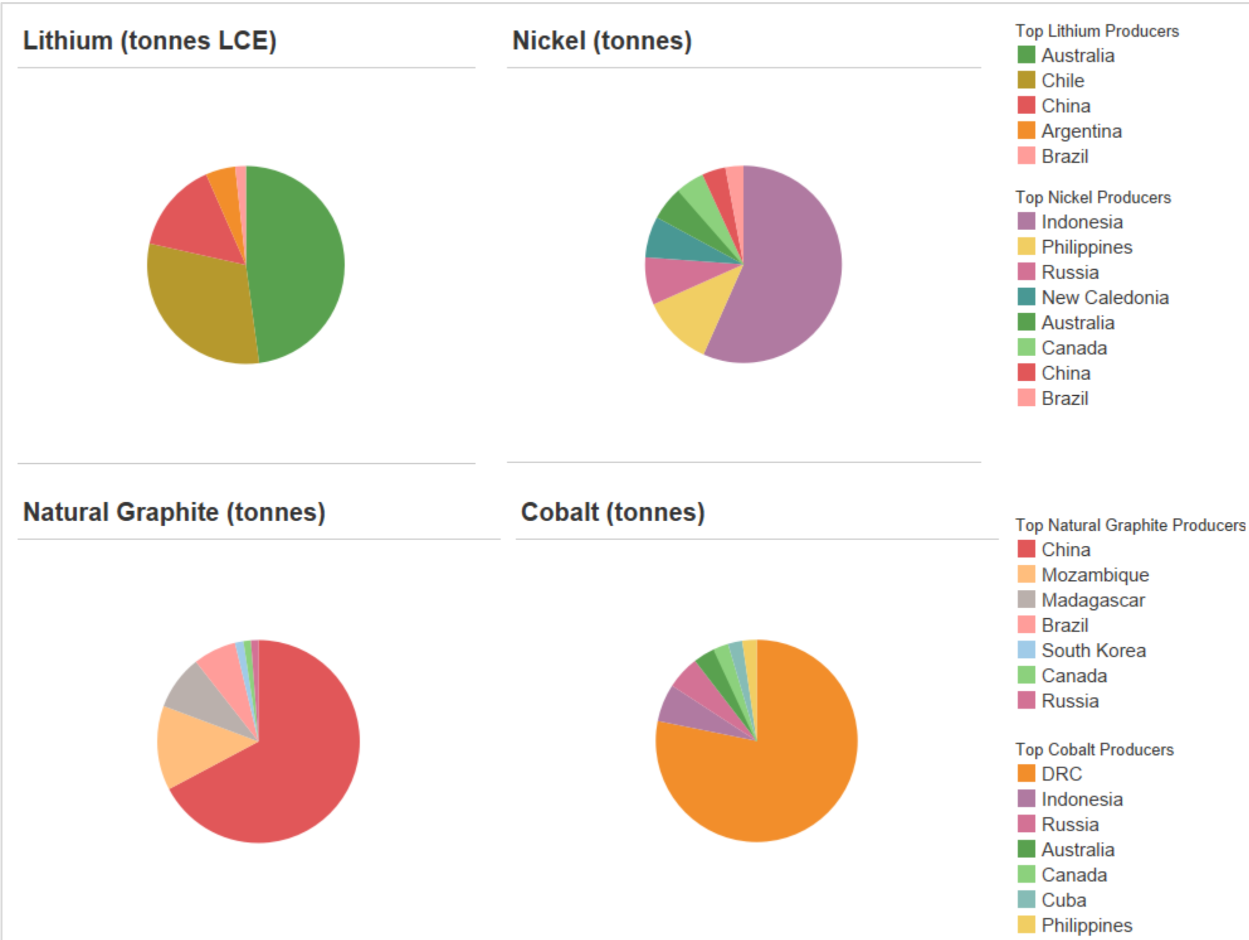

Figure 7. Leading mining producers of key critical materials by 2022.
Source: Data from USGS, 2023.
Note: Lithium is in contained tonnes of lithium carbonate equivalent (LCE) while other materials are in contained tonnes of metal. Data last updated September 2023 (February 2024 domestic).

ANL conducted an analysis of prospective mining projects across various countries, focusing on both the near-term (2025) and medium-term (2030 to 2035) prospects. Indonesia and the DRC are projected to retain their leading roles in the production of nickel and cobalt, respectively. However, the production landscape for lithium and natural graphite is expected to diversify, with new major producers emerging (See Figure 8). For example, should all anticipated projects be operational by 2030, the U.S. has the potential to account for nearly a quarter of the global lithium production.

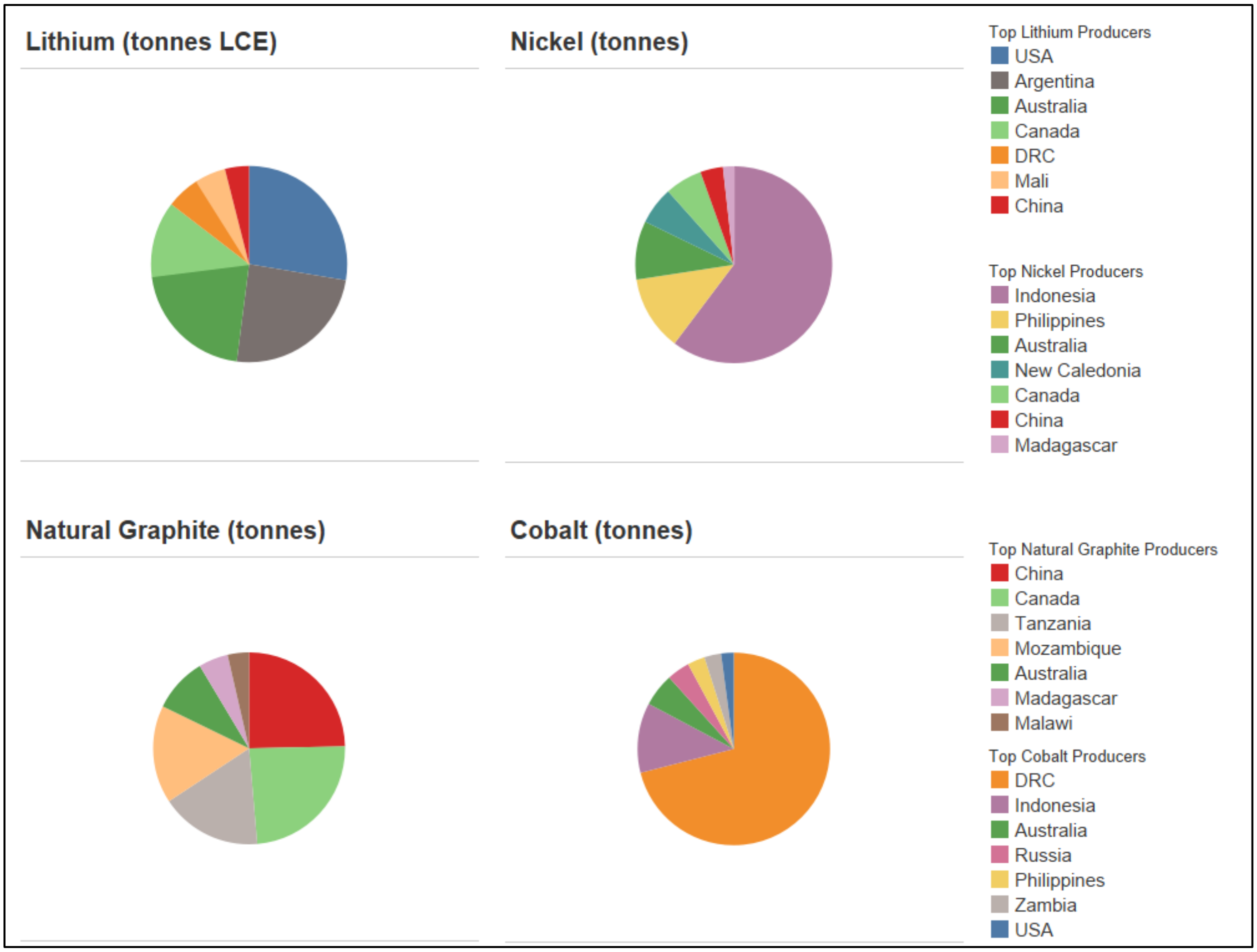

Figure 8. Prospective leading producers of key critical minerals by 2030.
Source: ANL estimates based on data compiled from USGS, S&P Global, company investor reports, technical reports, press releases, and news journals.
Note: Lithium is in contained tonnes of lithium carbonate equivalent (LCE) while other materials are in contained tonnes of metal. Data last updated September 2023 (February 2024 domestic).

Domestic recycling potential

Given current technology, the U.S. has limited economically viable critical mineral resources, particularly nickel, cobalt, manganese, and graphite. Considering this geological limitation, recycling presents one of the practical solutions to meeting the projected demand for new batteries. Notably, recycling has a lesser environmental footprint, and faces fewer hurdles in establishing facilities compared to mining operations (Broadbent et al., 2016; Fujita et al., 2022; and Hagelüken & Goldmann, 2022).

The battery materials recycling industry in the U.S. is nascent. However, with a multitude of initiatives in progress to expand the industry, a transformation is anticipated soon.[15,16]

15 https://www.anl.gov/li-bridge
16 https://www.energy.gov/eere/vehicles/federal-consortium-advanced-batteries-fcab

Recycling feedstock is expected to consist of batteries reaching the end of their lifespan and those reclaimed from battery manufacturing waste. This feedstock is projected to make a substantial contribution to the future supply of battery material.

Enhancing the recycling process for these feedstocks will require advancements in recycling technologies, and development of efficient logistical strategies for the collection and transportation of these materials to recycling facilities (Bae & Kim, 2021; Toro et al., 2023; and Zheng et al., 2023). This process may require collaboration between recyclers and manufacturers.[17, 18] This report assesses the potential quantity of battery materials that could be available over time to supplement the demand for raw materials. More detailed discussions on recycling potential can be found in Sections II and IV.

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17 https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-recycling-takes-the-drivers-seat

18 Logistical challenges associated with EV battery recycling are described in detail in California's Lithium-ion Car Battery Recycling Advisory Group Final Report. Lithium-ion Car Battery Recycling Advisory Group

II. U.S. LANDSCAPE FOR DOMESTIC AND INTERNATIONAL EFFORTS IN SECURING CRITICAL MATERIALS

The U.S landscape for securing critical materials is a dynamic interplay of domestic initiatives and international partnerships. While certain materials like lithium have known economically viable resources within the U.S, others such as manganese and natural graphite have limited domestic resources that can be accessed with current technology. As a result, these materials will require sourcing from international markets.

a. Domestic landscape

The U.S has been making concerted efforts to enhance the production of critical materials through both mining and recycling. This includes modernizing the U.S. Mining Law of 1872[19] and streamlining permitting processes under the Federal Permitting Improvement Steering Council (FAST-41).[20] Additionally, BIL and IRA have introduced several incentives to scale domestic processing and recycling of critical minerals. These incentives include grants, such as the $3 billion Battery Manufacturing and Recycling Grant Program,[21] and tax credits, such as 45X and 48C. In 2022, approximately $2.8 billion of BIL funding was invested in the battery supply chain, including processing and recycling, across the country (See Figure 9).[22]

Scaling domestic mining supply

Complementing select mining investments through the Defense Production Act (DPA), midstream and downstream investments are expected to incentivize upstream operations. Companies are competing to secure materials to feed domestic mid-stream operations, such as processing, cathode, and anode production. As of January 2024, 663 facilities across the battery supply chain, including 79 facilities for electrode and cell manufacturing, and 63 facilities for battery grade components manufacturing, are in various stages of development across the U.S.[23] New battery manufacturing and supply chain investments total more than $120 billion, with over 80,000 potential new jobs.[24] DOE estimates that announced battery cell factories could supply batteries for more than 10 million new EVs every year.[24] Furthermore, other provisions, such as domestic content requirements in IRA (e.g., 30D), or statutory language limiting battery supply chains from FEOC in both IRA and BIL, are anticipated to incentivize domestic upstream

19 https://www.doi.gov/pressreleases/biden-harris-administration-report-outlines-reforms-needed-promote-responsible-mining

20 https://www.permits.performance.gov/fpisc-content/permitting-council-moves-designate-critical-minerals-supply-chain-fast-41-sector

21 https://www.energy.gov/mesc/battery-manufacturing-and-recycling-grants

22 https://www.energy.gov/sites/default/files/2022-10/DOE%20BIL%20Battery%20FOA-2678%20Selectee%20Fact%20Sheets%20-%201_2.pdf

23 https://www.nrel.gov/transportation/li-ion-battery-supply-chain-database-access.html

24 https://www.energy.gov/invest?utm_campaign=&utm_content=1705068720&utm_medium=U.S.+Department+of+Energy+%28DOE%29

operations. Following the enactment of IRA, numerous investments in battery minerals have been announced across the country.[24] Notable examples include the Kings Mountain lithium project by Albemarle in North Carolina and the Smackover lithium project by ExxonMobil and Tetra Technologies in Arkansas. Aside from the IRA, EXIM is supporting upstream and mid-stream critical minerals projects in the U.S. and abroad through a host of financing products including direct loans, loan guarantees, and export credit insurance.[25]

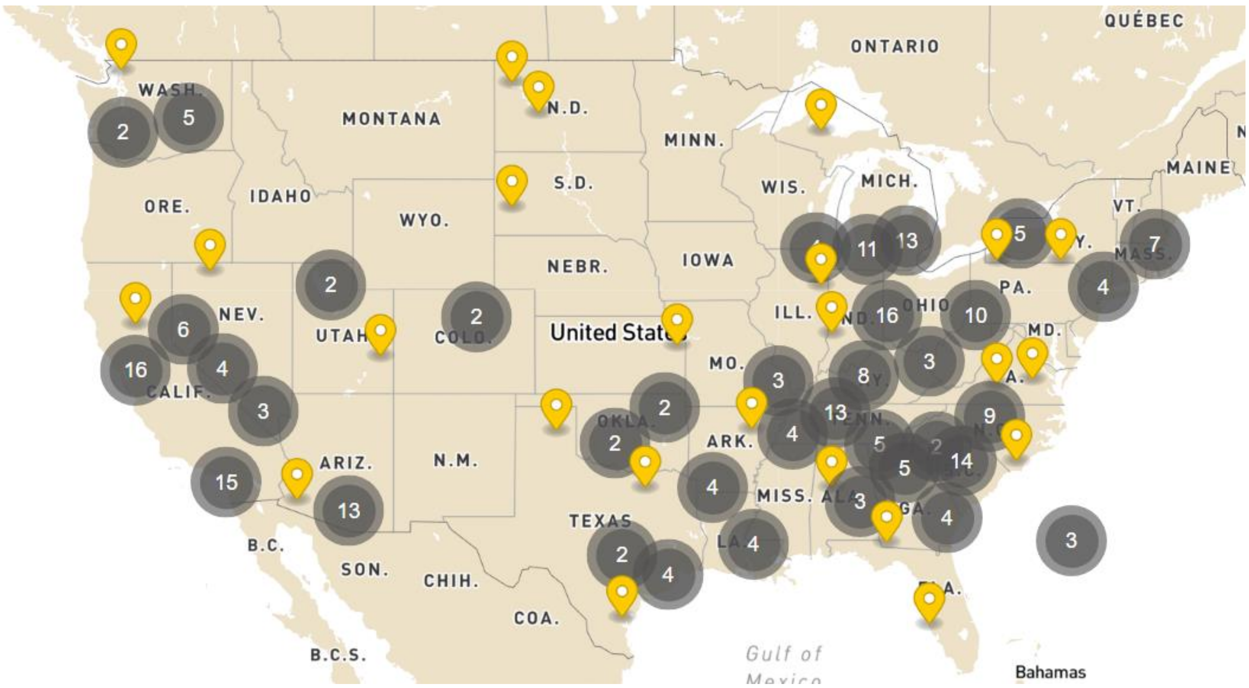

Figure 9. Map of New U.S. battery manufacturing and supply chain investments.
Investments announced during Biden-Harris administration, updated January 2024. Yellow balloons represent individual investments in the battery supply chain. Gray bubbles with numbers represent multiple investments in a similar geographic area.
Source: DOE 2024.

Efforts to scale domestic supply of minerals are underway across government entities. The USGS is leading numerous projects under the Earth Mapping Resources Initiative (Earth MRI) to improve mapping and exploration of domestic resources, including already-announced or in-progress projects in Alabama, Florida, New York, Montana, Kentucky, Tennessee, Georgia, and across the U.S. Southwest including projects focused on Arizona and Nevada.[26] Additionally, BIL is funding a new USGS research center focused on energy and minerals at the Colorado School of Mines.[27] The National Aeronautics and Space Administration (NASA) Earth Surface Mineral Dust Source Investigation (EMIT) sensor is creating detailed global maps of ten key surface minerals based on dust particles which could be used to detect rare-earth elements or lithium-

25 https://www.exim.gov/about/special-initiatives/ctep/critical-minerals

26 https://ngmdb.usgs.gov/emri/#3/40/-96

27 https://www.usgs.gov/special-topics/bipartisan-infrastructure-law-investments/science/energy-and-minerals-research

bearing minerals.[28] Further, the House Committee Report associated with the FY24 NDAA requested by March 1, 2024 a report on domestic resources, mining, and processing capabilities for deep-sea polymetallic nodules that may reduce reliance on foreign adversaries for critical minerals.[29] Relatedly, in December 2023, the U.S. Extended Continental Shelf (ECS) Project, a collaboration between the Department of State, National Oceanic and Atmospheric Administration (NOAA) and the USGS, announced the outer limits of the U.S. ECS.[30] Subsequent to the establishment of these limits, Congress may consider the advantages and disadvantages of the U.S. accession to the United Nations (U.N.) Convention on the Law of the Sea (UNCLOS), given USGS reporting that high concentrations of critical minerals may serve national security interests.[31] The International Seabed Authority (ISA), an intergovernmental body created by UNCLOS, is in the process of creating regulations related to deep sea mining; concerns over impacts to marine ecosystems, including marine mechanisms to store carbon, have been a focus.[32]

The FY24 National Defense Authorization Act (NDAA) created the Intergovernmental Critical Minerals Task Force to facilitate coordination for data sharing, capacity building, workforce development, policy review, environmental responsibility, onshoring opportunities, and identifying alternatives. The FY24 NDAA also directs the U.S. Department of Defense (DOD) to develop a University Affiliated Research Center for Critical Minerals.[33] USGS, DOD, and DOE are collaborating on a series of "hackathons" to leverage AI and machine learning to domestic critical minerals resource assessment.[34]

Innovation in battery materials

The U.S. has also invested substantially in battery technology innovation. Innovations in battery technology have the potential to reduce demand for key minerals, or shift demand to other, more accessible materials. For example, the U.S. Department of Energy (DOE) is prioritizing the reduction or elimination of the use of cobalt in batteries and a consortium of scientists led by Berkeley Lab is focused on making cathodes from cheaper, more abundant alternatives to nickel and cobalt.[35] Pacific Northwest National Laboratory (PNNL) is partnering with Microsoft to use AI to identify new battery materials.[36] A recent discovery through this partnership found a new material for electrolyte that reduces the amount of lithium needed for the battery and allowed for electrolyte material synthesis in months rather than decades. ANL has invented and patented a new

28 https://www.nasa.gov/missions/emit/nasa-sensor-produces-first-global-maps-of-surface-minerals-in-arid-regions/

29 https://www.congress.gov/118/crpt/hrpt125/CRPT-118hrpt125.pdf#page=269

30 https://crsreports.congress.gov/product/pdf/R/R47912

31 https://crsreports.congress.gov/product/pdf/R/R47912

32 https://www.isa.org.jm/the-mining-code/

33 https://www.congress.gov/bill/118th-congress/house-bill/2670/text; Section 227.

34 https://www.whitehouse.gov/briefing-room/statements-releases/2023/11/27/fact-sheet-president-biden-announces-new-actions-to-strengthen-americas-supply-chains-lower-costs-for-families-and-secure-key-sectors/

35 https://newscenter.lbl.gov/2023/09/11/new-consortium-to-make-ev-batteries-more-sustainable/

36 https://news.microsoft.com/source/features/sustainability/how-ai-and-hpc-are-speeding-up-scientific-discovery/

cathode material that replaces lithium ions with sodium.[37] Scientists at ANL are also are piloting Lithium-Sulfur batteries, and in January 2024 DOE's Vehicle Technologies Office (VTO) granted millions to projects developing Li-S batteries – Sulfur is cost effective, abundant, and can hold more energy than traditional ion-based batteries.[38] PNNL has also made strides in developing silicon anodes, which if deployed could reduce the amount of graphite needed for the EV transition.[39] Through the 2022 CHIPS and Science Act, the Department of Commerce and the National Science Foundation are funding critical minerals and battery materials research, innovation, and workforce development activities in New York, Nevada, Utah, and Missouri.[40] The United States Advanced Battery Consortium, supported by DOE, is focused on research and development (R&D) for EV batteries using earth-abundant and domestically available battery materials.[41]

Scaling domestic recycling

Recycling facilities are primarily divided into two categories: Intermediate Processing Facilities (IPFs) and Recycled Material Producers (RMPs). IPFs receive lithium-ion batteries and batteries manufacturing scrap, processing these materials into a substance known as 'black mass' RMPs, on the other hand, process black mass into materials that can be reintegrated into the battery supply chain.

An analysis by the Federal Consortium for Advanced Batteries Group 4 (Recycling and Second Use) reveals an overproduction of black mass that exceeds the handling capacity of current domestic recyclers. This surplus is subsequently shipped overseas to recyclers equipped to manage it. The rapid construction and commission of IPFs coupled with presence of established foreign RMPs, has led to a mismatch in the domestic recycling supply chain.

Foreign entities, with their longstanding investments in pyrometallurgical, hydrometallurgical, and direct recycling facilities, have existing relationships with battery material producers in their respective locations. This facilitates the reintegration of recycled materials back into the international battery supply chain. The demand for black mass from IPFs by foreign RMPs, along with their capacity to produce recycled materials, generates the necessary off-take from domestic IPFs. However, this also slows the expansion of domestic RMPs.

However, in the past two years, several incentives have been introduced to scale domestic recycling, including through the Loan Programs Office (LPO) and 48C, as part of both BIL and IRA manufacturing investments (Barlock, 2023). Consequently, 2023 saw numerous announcements regarding the expansion of recycling capacity in the U.S. For example, in early

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37 https://www.anl.gov/article/cathode-innovation-makes-sodiumion-battery-an-attractive-option-for-electric-vehicles

38 https://www.anl.gov/article/lithiumsulfur-batteries-are-one-step-closer-to-powering-the-future

39 https://www.pnnl.gov/news-media/leap-using-silicon-battery-anodes

40 https://www.eda.gov/news/press-release/2023/10/23/biden-harris-administration-designates-31-tech-hubs-across-america; https://new.nsf.gov/funding/initiatives/regional-innovation-engines/portfolio/upstate-new-york-energy-storage-engine

41 https://uscar.org/usabc/

2023, LPO offered a conditional loan commitment of $2 billion to Redwood Materials to support the construction and expansion of a battery materials facility that will produce critical EV battery components from an increasing use of recycled materials.[42] Additionally, LPO announced a conditional commitment to Li-Cycle for a $375 million loan to help finance the construction of a first-of-its-kind lithium-ion battery resource recovery facility in North America.[43] In November 2022, DOE announced selectees for the Bipartisan Infrastructure Law (BIL) Electric Drive Vehicle Battery Recycling and Second Life Applications grant program, awarding more than $45 million to 5 projects in 5 states for research, development, and demonstration of electric vehicle battery recycling.[44]

At the federal level, the Federal Consortium for Advanced Batteries (FCAB) has assembled Federal agencies committed to ensuring a domestic supply of lithium-ion batteries and accelerating the development of a robust and secure domestic industry. One working group within FCAB specifically focuses on the recycling and reuse of batteries. The 2023 NDAA included a provision directing the federal government to develop a strategy to recycle and recover minerals from batteries used in the federal electric vehicle fleet.

Figure 10 presents the Fiscal Year 2023 analysis of domestic existing and planned recycling capacity for the two recycling supply chain segments, IPF and RMP. By late 2023, the FCAB recycling and reuse working group tracked 174,500 tons of existing IPF capacity and an additional 197,500 tons of planned capacity over the next 2 to 4 years for processing lithium-ion batteries (and manufacturing scrap). The largest companies with existing or planned IPFs are Li-Cycle, Interco, American Battery Technology Company, Ascend Elements, and Cox Automotive (parent company of Spiers New Technologies). FCAB also identified 35,000 tons of existing capacity and an additional 76,000 tons of planned capacity over the next 2 to 4 years. The main RMPs with existing or planned capacity are American Battery Technologies Company, Ascend Elements, Li-Cycle, and Redwood Materials.

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42 https://www.energy.gov/lpo/articles/lpo-offers-conditional-commitment-redwood-materials-produce-critical-electric-vehicle

43 https://www.energy.gov/lpo/articles/lpo-announces-conditional-commitment-loan-li-cycles-us-battery-resource-recovery

44 https://www.energy.gov/infrastructure/electric-drive-vehicle-battery-recycling-and-2nd-life-apps

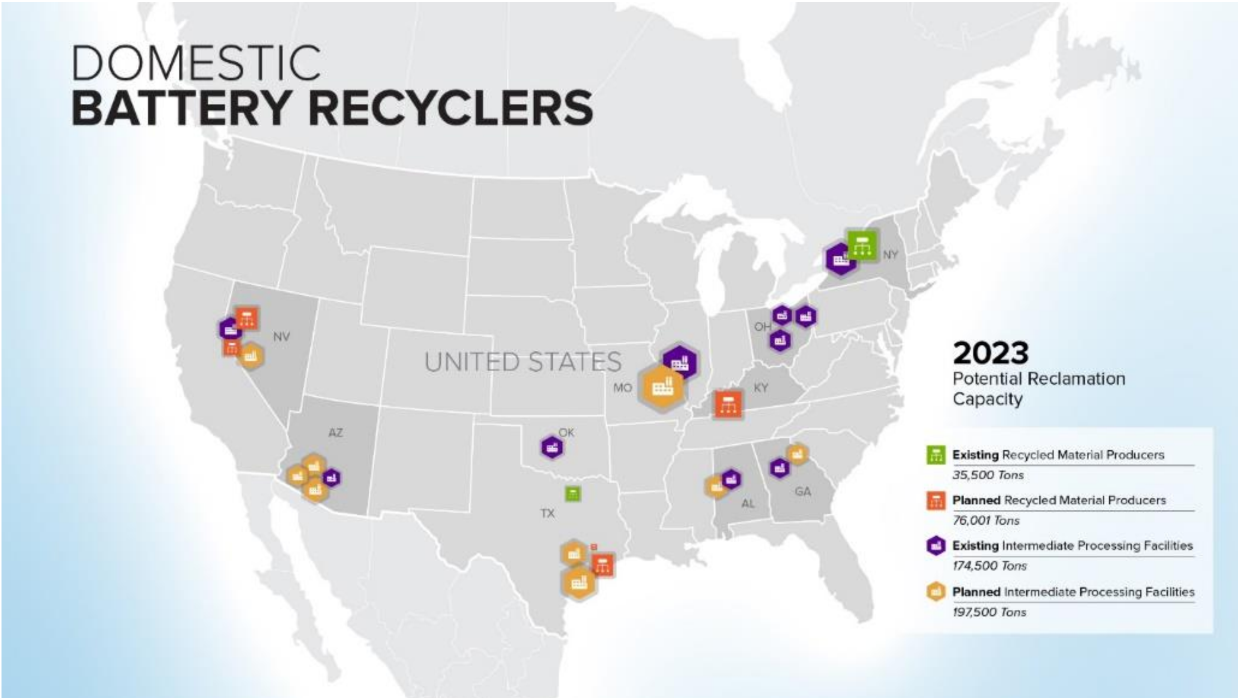

Figure 10. Location and Size of Intermediate Processing Facilities and Recycled Materials Producers in the United States. Updated October 1, 2023.

b. International landscape

On the international front, the U.S. is actively working to secure materials to supplement domestic supply in line with demand projections. Trading patterns for critical materials will need to be expanded and adjusted to serve the emerging battery industry in the U.S. This analysis highlights the potential substantial quantity of new mineral production capacity both domestically and internationally, and opportunities to diversify trade flows for critical materials. The U.S effort to expand and diversify sourcing involves strengthening existing trade agreements and actively strengthening existing alliances with new efforts centered around economic development, technology sharing, and regional security (See examples in Figure 11). Producers involved in the battery supply chain, both domestically and globally, are already modifying trading patterns, partly in response to sourcing restrictions embedded within different domestic incentives (see section I(a)). For example, U.S. manufacturers are structuring offtake agreements that meet IRA incentive requirements, substituting supplies from foreign entities of concern (FEOC) with those from friendly countries.[45] With a broad set of diversified materials pathways, U.S. manufacturers have a prime opportunity use these agreements and initiatives to collaborate with international partners and allies for an expanded and consistent mineral supply.

45 https://www.energypolicy.columbia.edu/publications/the-ira-and-the-us-battery-supply-chain-one-year-on/

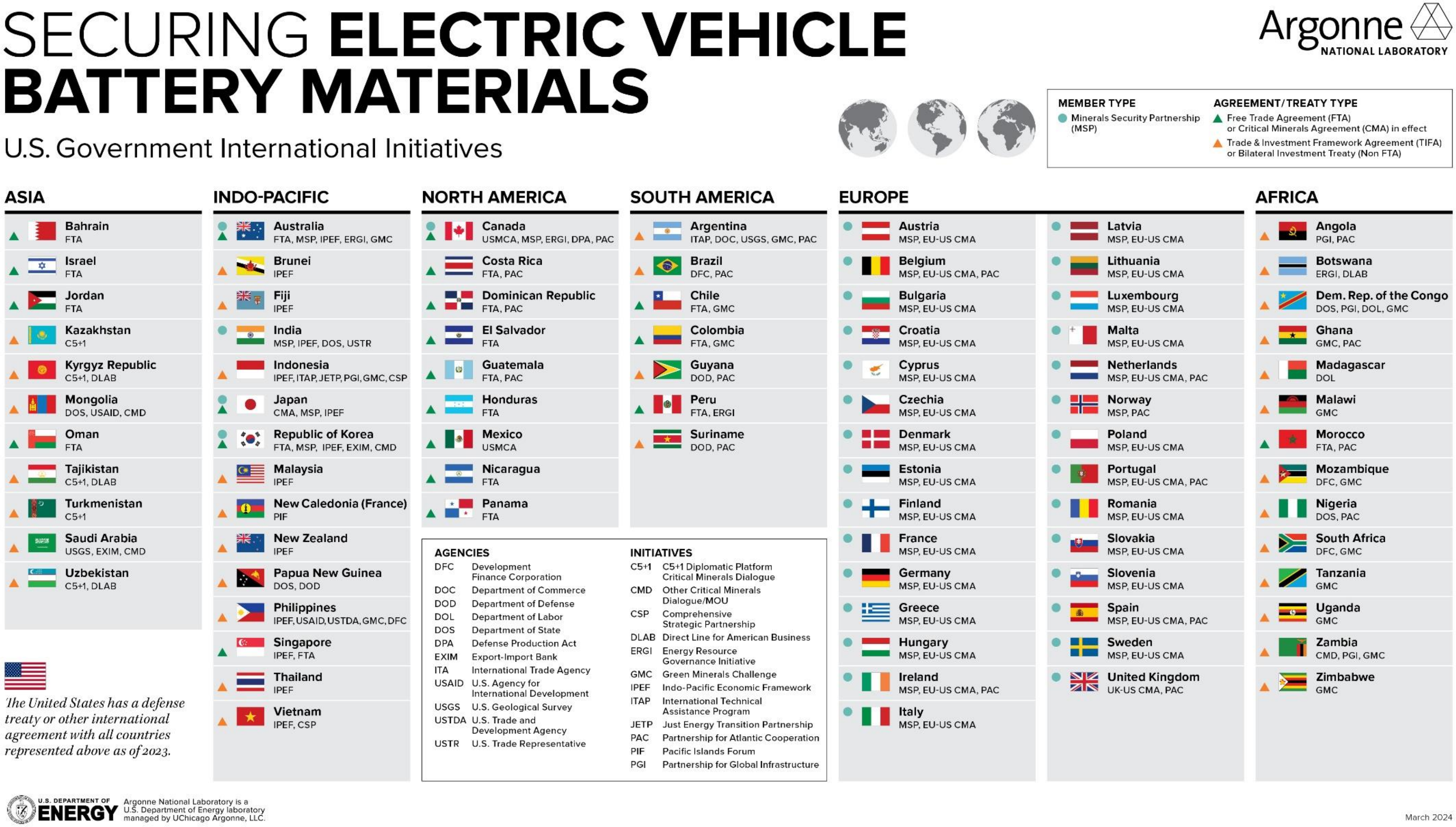

Figure 11. U.S. Government international initiatives to secure battery minerals and materials.

U.S. Government initiatives aimed at shifting the trade landscape can reduce risk in international supply chains and enhance the resilience of the rapidly growing domestic battery industry (Gohlke et al., 2024), while simultaneously supporting the economies of its partners and allies.

Building on domestic efforts, the U.S. possesses a significant and growing portfolio of international engagements to secure minerals supplies including FTAs, Mineral Security Partnership (MSP), Trade Investment Framework Agreements (TIFAs), and other bilateral and multilateral agreements including the Partnership for Global Infrastructure and Investment (PGI) (See examples in Figure 11). In the words of Assistant Secretary of State for Energy Resources Geoffrey R. Pyatt in June 2023, "The Biden-Harris Administration is using all the tools at its disposal, such as investments, loan programs, public-private partnerships, and technical assistance for energy infrastructure and supply chain development."[46] Government entities, including the White House, U.S. Agency for International Development (USAID), U.S. Development Finance Corporation (DFC), U.S. Export-Import Bank (EXIM), and the Departments of Defense, State, Commerce, Labor, Interior, and Energy, have been engaged in these efforts. These agencies have engaged governments in Asia, Africa, Europe, South America, and Australia, with engagements spanning investment, cooperative agreements, anti-corruption efforts, research, and economic development. Non-exhaustive examples of recent activity in this area include:

- The White House announced the IPEF Critical Minerals Dialogue, an initiative to support U.S. expansion and development of the critical mineral supply chain. IPEF is the Indo-Pacific Economic Framework for Prosperity (IPEF), a partnership between Australia, Brunei, Fiji, India, Indonesia, Japan, Republic of Korea, Malaysia, New Zealand, the Philippines, Singapore, Thailand, and Viet Nam.[47] More broadly, the IPEF's pillars spanning trade, supply chains, clean economy, and fair economy form a foundation to ensure tangible benefits that fuel economic activity and investment, promote sustainable and inclusive economic growth, and benefit workers and consumers across the region.[48] The IPEF Supply Chain Agreement entered into force on February 24, 2024.[49]

- The State Department also sent delegations to Chile, the Philippines, and South Korea, led by Under Secretary Jose W. Fernandez, to strengthen cooperation around critical mineral supply chains.[50]

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46 https://docs.house.gov/meetings/FA/FA00/20230614/116025/HHRG-118-FA00-Wstate-PyattG-20230614.pdf

47 https://www.whitehouse.gov/briefing-room/statements-releases/2023/11/16/fact-sheet-in-san-francisco-president-biden-and-13-partners-announce-key-outcomes-to-fuel-inclusive-sustainable-growth-as-part-of-the-indo-pacific-economic-framework-for-prosperity/

48 https://www.commerce.gov/ipef

49 https://www.commerce.gov/news/press-releases/2024/01/us-department-commerce-announces-upcoming-entry-force-ipef-supply-chain

50 https://www.state.gov/under-secretary-fernandezs-travel-to-vietnam-the-philippines-and-the-republic-of-korea/; Under Secretary Fernandez's Travel to Chile, Uruguay and Paraguay - United States Department of State

- The State Department launched the Minerals Investment Network for Vital Energy Security and Transition, or MINVEST, in 2023: a public-private partnership between the U.S. Department of State and SAFE Center for Critical Minerals Strategy to spur investment in mining, processing, and recycling opportunities.[51] The State Department's ambassadors and commercial experts also connect U.S. companies with mining and opportunities internationally through the Direct Line for American Business program.[52]

- The White House and the European Union together announced support for the Lobito Corridor, which connects the Democratic Republic of the Congo and Northwest Zambia to regional and global trade through the Port of Lobito in Angola. The corridor will reduce transport time, lower costs, and reduce the carbon footprint of metals exports from the region. The United States and the E.U. also intend to support sustainable economic development in the three countries, including clean energy projects and supporting diversified investment in critical minerals and clean energy supply chains.[53] In February 2024, the MSP announced the signing of an MOU between DRC's state mining company, Gecamines, and the Japan Organization for Metals and Energy Security (JOGMEC), to collaborate on exploration, production, and processing of critical minerals in the DRC.[54] Shortly thereafter, Gecamines announced the transfer of exclusive mining rights for five mining areas to its subsidiary Entreprise Generale du Cobalt (EGC); EGC Chairman describes this action as "the beginning of the standardization of artisanal cobalt mining," which has been linked to human rights violations.[55]

- The U.S. Trade Representative facilitated an agreement between the U.S. and India to develop a roadmap on critical minerals and supply chains to increase cooperation and achieve economically meaningful outcomes.[56]

- The USGS collaborated with the federal geological surveys of Canada and Australia to release a compilation of minerals resource datasets.[57]

- USAID granted funds through the Just Energy Transition Green Minerals Challenge to 11 partners across 15 countries throughout Africa, Asia, and Latin America, to combat

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51 https://www.state.gov/minvest

52 https://www.state.gov/direct-line-for-americanbusiness/

53 https://www.whitehouse.gov/briefing-room/statements-releases/2023/09/09/joint-statement-from-the-united-states-and-the-european-union-on-support-for-angola-zambia-and-the-democratic-republic-of-the-congos-commitment-to-further-develop-the-lobito-corridor-and-the/

54 https://www.state.gov/the-minerals-security-partnership-announces-collaboration-in-minerals-exploration-production-and-processing-between-gecamines-in-the-democratic-republic-of-the-congo-and-jogmec-in-japan/

55 https://www.reuters.com/markets/commodities/congos-gecamines-entreprise-generale-du-cobalt-sign-mining-deal-2024-02-07/

56 https://ustr.gov/about-us/policy-offices/press-office/press-releases/2024/january/joint-statement-united-states-india-trade-policy-forum

57 https://www.usgs.gov/news/technical-announcement/australia-canada-and-us-unify-critical-minerals-data

corruption and increase transparency and integrity in global critical minerals supply chains.[58]

- DOI, through its International Technical Assistance Program, is working with partners around the world to advance technical capacity and improve governance for clean energy minerals projects. Recent work includes working with Argentina to build capacity for sustainable lithium development.[59]

- USAID, in collaboration with the U.S. Commercial Service, formalized a $5 million technical assistance program to develop the Philippines' critical minerals sector.[60]

- In September 2023, President Biden met with the presidents of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan (C5+1), launching the C5+1 Critical Minerals Dialogue and committing to principles of partnership. The Dialogue aims to strengthen economic cooperation, support sustainable development, and advance the development of a robust minerals industry in the region.[61]

- The U.S. Trade and Development Agency (USTDA), which advances economic development and U.S. export opportunities abroad, recently accepted proposals for a contractor to assess potential critical minerals projects in Sub-Saharan Africa.[62]

Recent policy recommendations from U.S. Congress highlight the desire for expanding and strengthening trade relationships with allies.[63] On December 12, 2023, the House Select Committee on US-China Competition released a series of policy recommendations. These included the authorization of a 'Resilient Resource Reserve' the advancement of trade agreements, the investigation of dumping practices, the restriction of exports from DOE/DOD-funded black mass processors, the enhancement of training programs, and the expansion of the MSP. A November letter from Senators Marco Rubio (R-FL) and Mark Warner (D-VA) to the President and Chair of the Board of Directors of EXIM exhorted the agency to prioritize projects to secure critical mineral supply chains in allied and partner nations.[64]

The 2024 National Defense Authorization Act signed on December 22, 2023 contains numerous provisions related to securing and diversifying the supply chain for critical materials, including directives to US Embassy Deal Teams "to identify and secure United States or allied

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58 https://www.usaid.gov/anti-corruption/document/powering-just-energy-transition-green-minerals-challenge

59 https://www.doi.gov/itap/energy-and-minerals

60 https://ph.usembassy.gov/partnership-launched-to-implement-u-s-funded-php280-million-program-for-philippine-critical-minerals-sector/

61 https://www.whitehouse.gov/briefing-room/statements-releases/2023/09/21/c51-leaders-joint-statement/

62 https://www.ustda.gov/business_opp_ustda/clean-energy-and-critical-minerals-desk-study-sub-saharan-africa/

63 https://selectcommitteeontheccp.house.gov/sites/evo-subsites/selectcommitteeontheccp.house.gov/files/evo-media-document/reset-prevent-build-scc-report.pdf

64 https://www.warner.senate.gov/public/_cache/files/1/7/17def9a2-d95c-40b1-9028-119f35769394/FCB942C1068EB79B54E8769260B13F59.11.16.23-rubio-warner-letter-to-exim-re-critical-minerals.pdf

government support of strategic projects, such as critical minerals development."[65] This NDAA directive builds upon existing efforts like the China and Transformational Exports Program at EXIM.[66] Relatedly, the NDAA directs DOD to partner with USAID and DFC to inventory gaps between U.S. and Chinese infrastructure investments around the globe, assess threats to critical minerals access and supply chain security, and identify opportunities to increase U.S. infrastructure investments in these areas. The NDAA also directs the State Department to lead a global cooperative framework to end human rights abuses in critical minerals sourcing and directs DOD to deliver a strategy to achieve critical minerals independence from covered nations by 2035. Finally, the 2024 NDAA directs the U.S. Trade Representative to report on plans to leverage partnership of the countries of the Quadrilateral Security Dialogue to secure global supply chains for critical minerals.

For the purpose of this analysis potential U.S. trading partners are categorized into four primary groups: countries with which the U.S. has an FTA, members of the MSP, countries that do not have an FTA agreement nor are partners of the MSP (Non FTA (Non MSP)), and countries that are considered a Foreign Entity of Concern as defined by the U.S. Department of Energy.[67] This classification aims to quantify the international trade dynamics to inform effective and secure sourcing strategies.

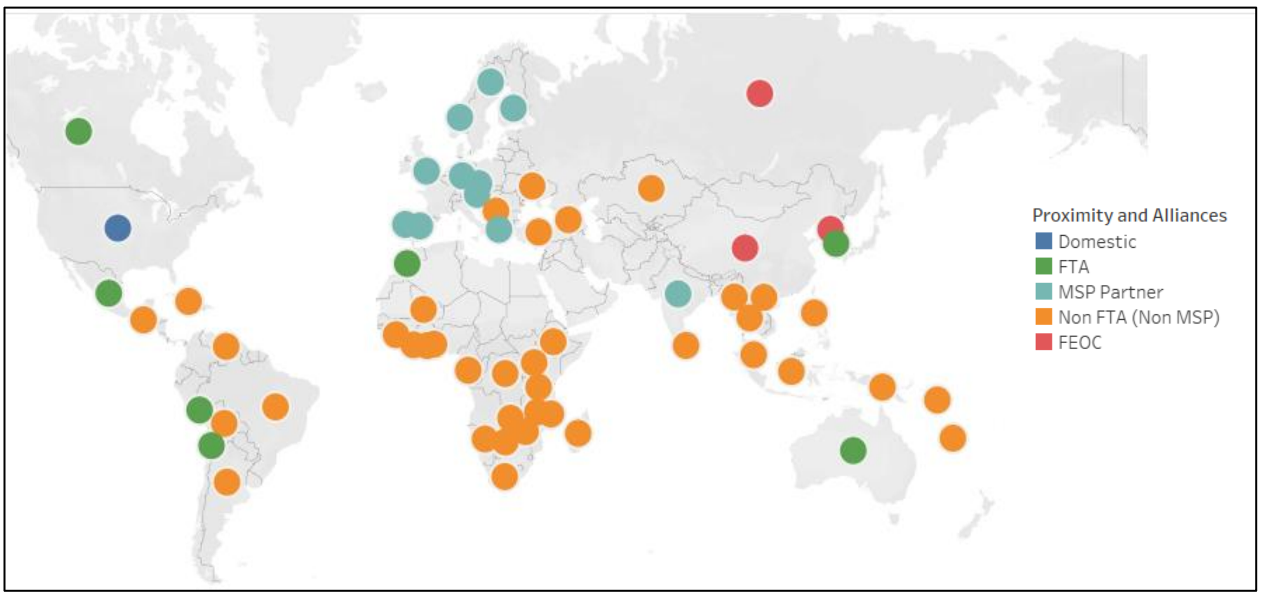

Figure 12. Distribution of the five minerals by 2030 based on current proximity and alliances with the U.S.

Source: ANL estimates based on data compiled from USGS, S&P Global, and company reports.
Note: Data for domestic project last updated February 2024, for international projects September 2023.

65 https://www.congress.gov/bill/118th-congress/house-bill/2670/text

66 https://www.exim.gov/about/special-initiatives/ctep

67 https://www.energy.gov/articles/department-energy-releases-proposed-interpretive-guidance-foreign-entity-concern-public

Free Trade Agreements (FTA) countries

Currently, the U.S. has Free Trade Agreements with 20 countries,[68] which provide greater market access through reduced or eliminated tariffs, intellectual property protection, and elimination of non-tariff barriers. Example of countries under FTA include Australia, Chile, South Korea, and Mexico and Canada under the U.S. Mexico Canada Agreement (USMCA). FTA countries have a significant potential critical mineral capacity, right behind non-FTA countries (See Figure 13). Examples of countries highly endowed with critical mineral resources that have historically been a source of U.S. imports include Australia, Chile, and Canada. In analyzing the role of trade in securing critical minerals supply chains, this study prioritizes access to minerals in the FTA countries over other partner countries. There are countries that both have an FTA with the U.S. and are a member of the MSP, e.g., Canada. For the sake of this analysis these countries are categorized as "FTA."

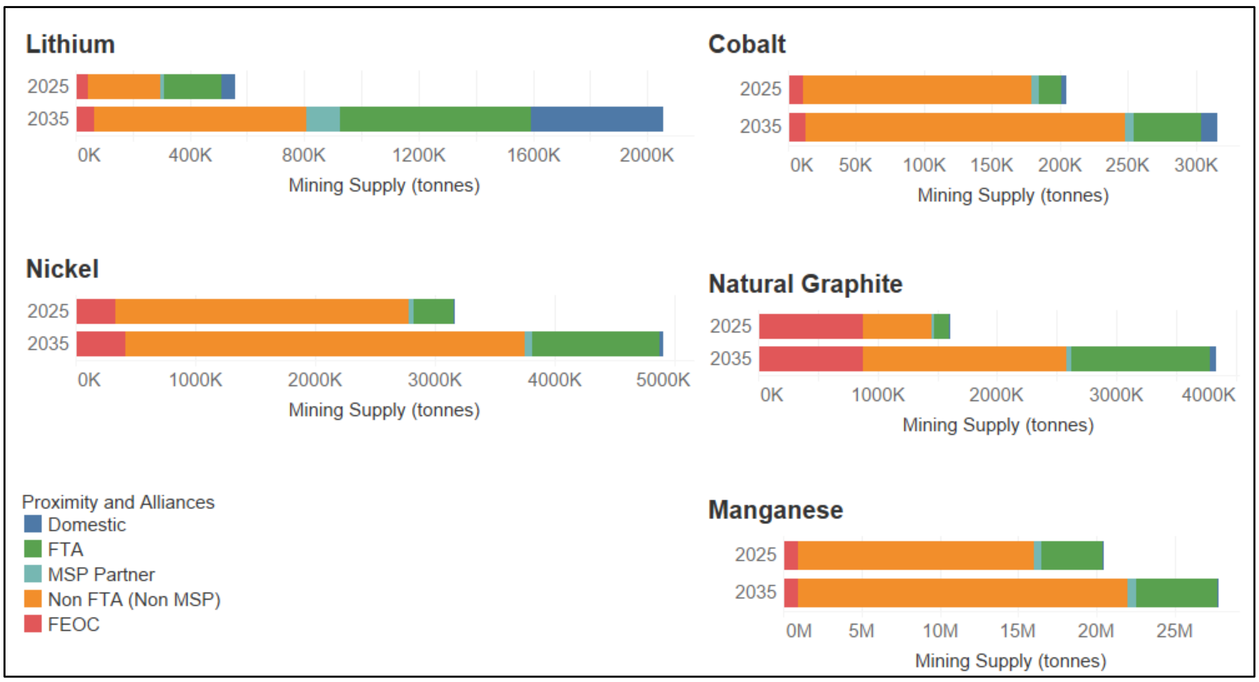

Figure 13. Prospective critical mineral capacity distribution by proximity and alliances.
Source: ANL estimates based on data compiled from USGS, S&P Global, and company reports.
Note: Lithium is in contained tonnes of lithium carbonate equivalent (LCE) while other materials are in contained tonnes of metal. Data for domestic project last updated February 2024, for international projects September 2023.

Minerals Security Partnership countries

The MSP is a collaboration of 13 countries and the EU to mobilize public and private investment to responsibly secure critical minerals supply chains globally. MSP partners include

68 Per https://ustr.gov/trade-agreements/free-trade-agreements, the U.S. has comprehensive free trade agreements in effect with Australia, Bahrain, Canada, Chile, Colombia, Costa Rica, Dominican Republic, El Salvador, Guatemala, Honduras, Israel, Jordan, Korea, Mexico, Morocco, Nicaragua, Oman, Panama, Peru, and Singapore.

Australia, Canada, Finland, France, Germany, India, Italy, Japan, Norway, the Republic of Korea, Sweden, the United Kingdom, the United States, and the European Union (represented by the European Commission).[69] Some of these countries such as Canada, Finland, Germany, and Norway have robust critical mineral resources. This study prioritizes access to materials located in the members of MSP over Non-FTA and FEOC countries in analyzing the role of trade in securing U.S. mineral supply chains. For sake of this analysis non-FTA countries who are MSP members are categorized as "MSP." It should be noted that the MSP projects in this analysis only include projects within the borders of MSP partners. MSP members do support projects located within and outside MSP partners' jurisdictions (both FTA and non-FTA countries). All specific projects that MSP member countries support outside their borders have not been publicly disclosed and are out of scope of this study.[70]

Non-Free Trade Agreements countries

Non-Free Trade Agreements (Non-FTA) countries are those with which the U.S. does not have a free trade agreement. Most of the current and future critical mineral capacity is located in non-FTA countries (See Figure 13). These countries do not have the same level of market access as FTA countries. Without the creation of bilateral or multilateral agreements aimed at propagating trade, commerce with these nations may be subjected to standard local and international trade rules. There are several bilateral and multilateral agreements in force with several non-FTA countries. For example, Democratic Republic of Congo (DRC) a leading producer of cobalt has had a bilateral investment treaty with the U.S. since 1989.[71] Another example of such agreements is the Trade and Investment Framework Agreements (TIFAs) which cover several resource rich countries such as: U.S. – Indonesia TIFA; US – Mozambique TIFA; U.S. – South Africa TIFA; U.S. – East Africa Community TIFA which includes DRC and Tanzania; and U.S. – Argentina TIFA.

There are also several trade agreements under negotiation where securing resilient U.S. supply chains is a key prong of the Administration's worker-centered trade agenda items.[72]

Countries associated with Foreign Entity of Concern (FEOC)

A FEOC is defined as being "owned by, controlled by or subject to the jurisdiction or direction" of a government of a covered foreign country.[73] The current covered nations are China, Russia, North Korea, and Iran. Both BIL and IRA statutes limit the participation of FEOCs in particular tax credits and grant programs: For example, in BIL the Battery Materials Processing and Battery Manufacturing and Recycling Grants prioritize non-FEOC supply chains. In the IRA,

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69 https://www.state.gov/minerals-security-partnership/

70 https://www.state.gov/joint-statement-on-the-minerals-security-partnership-announce-support-for-mining-processing-and-recycling-projects/

71 https://tcc.export.gov/Trade_Agreements/Bilateral_Investment_Treaties/index.asp

72 https://ustr.gov/trade-agreements/agreements-under-negotiation

73 https://www.energy.gov/articles/department-energy-releases-proposed-interpretive-guidance-foreign-entity-concern-public

the 30D Clean Vehicle Credit has language designed to restrict tax credit qualification of EV batteries that contain minerals that were extracted, processed, or recycled by FEOCs.[74]

74 https://www.federalregister.gov/documents/2023/12/04/2023-26513/section-30d-excluded-entities

III. DOMESTIC DEMAND OUTLOOK

This section describes U.S. battery material demand for EVs and ESS in gigawatt-hours (GWh) under high and low cases.

a. Anticipated battery demand from electric vehicles and energy storage systems

This analysis considers two scenarios, namely "ANL-High" and "ANL-Low" (See methodology used in Appendix I: Demand Projections Methodology, for more details). ANL-High presents an U.S. EV sales trajectory that aligns with the decarbonization goal for net-zero emissions in the energy economy by 2050 and serves as an upper limit. ANL-Low presents a U.S. EV sales trajectory that aligns with market dynamics. Both scenarios are consistent with President Biden's target of achieving a 50% EV sales share by 2030.

Figure 14 illustrates the sales of Battery Electric Vehicles (BEVs) for Light-Duty Vehicles (LDVs) and Medium- and Heavy-Duty Vehicles (MHDVs) under low and high scenarios. In ANL-High, the BEV sales share of LDV escalates to 72% in 2030 and reaches 100% by 2035, while the BEV sales share of MHDV climbs to 33% in 2030 and 74% in 2035. In ANL-Low, the BEV sales share reaches of LDV reaches 50% in 2030 and 69% in 2035, while the BEV sales share of MHDV increases to 7% in 2030 and 25% in 2035. This is consistent with DOE National Energy Modeling System-based analysis of electric vehicle sales in the 2030 timeframe associated with implementing the BIL and IRA.[75]

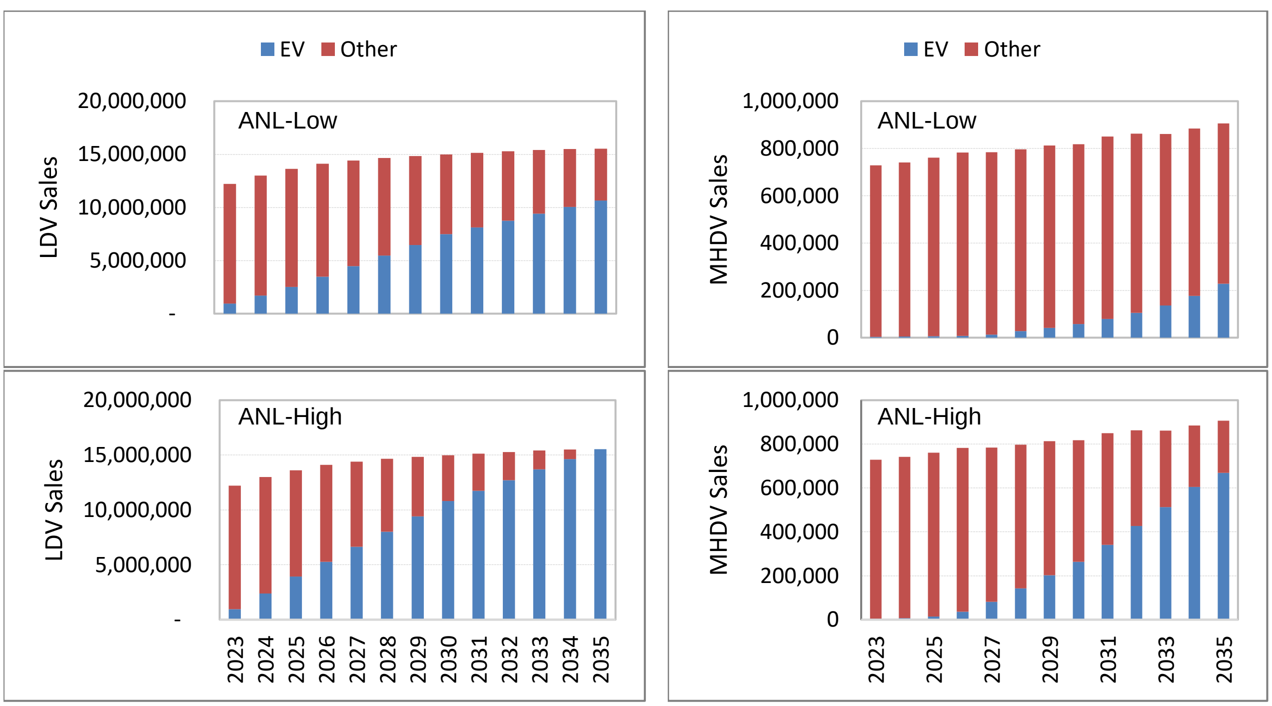

Figure 14. EV sales for LDV and MHDV under Low and High scenarios.

75 https://www.energy.gov/sites/default/files/2023-08/DOE%20OP%20Economy%20Wide%20Report_0.pdf

ESS demand is informed by National Renewable Energy Laboratory (NREL) modeling in Cambium (Gagnon et al., 2023). ANL-Low utilizes the Cambium 2022 Mid Case as a central estimate for inputs that incorporates electric sector policies as they stood in September 2022 and technology assumptions from the 2022 NREL Annual Technology Baseline (Gagnon et al, 2023). In contrast, ANL-High employs the Cambium 2022 Low Renewable Energy and Battery Cost Case to reflect electricity and battery tax credits under the Inflation Reduction Act.

The Cambium modeling includes grid-scale energy storage from batteries and indicates the total installed battery capacity. This total capacity is then translated into an annual demand for new installations, based on the assumption that battery installations have a maximum lifespan of 15 years (Cole & Karmarkar, 2023). The study also assumes that 5% of all installations will require annual replacement due to premature failure. ANL-Low assumes that lithium-ion batteries constitute 50% of the total battery capacity. Conversely, ANL-High suggests that 75% of ESS is fulfilled by lithium-ion batteries.

Figure 15 projects battery demand from EVs and ESS in the U.S. under both scenarios. ANL-Low projects battery demand to increase by 7x by 2030 and 10x by 2035 relative to 2023 levels. ANL-High projects a 15x increase by 2035 relative to 2023 levels. Notably across these projections, EVs consistently account for ~90% of the total battery demand.

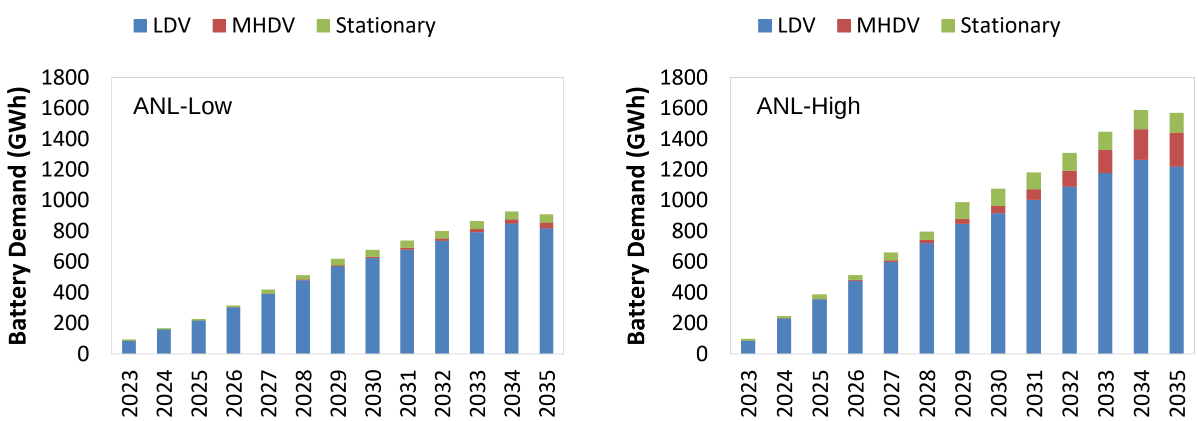

Figure 15. Projected Battery Demand from EVs and ESS under Low and High scenarios.

b. Anticipated material demand from electric vehicles and energy storage systems

Projections of material demand (tonnes or thousand tonnes) are derived from battery demand (GWh) per Figure 15 and the material content per kilowatt-hour (kWh) of various battery technologies entering the market. Material intensities for each technology leverages the Battery Performance and Cost (BatPaC) model (Knehr et al., 2022; Argonne National Laboratory, 2023). Material demand detail is found in Appendix I: Demand Projections Methodology.

Figure 17 to Figure 21 overview total demands for lithium, nickel, manganese, cobalt, and graphite required to satisfy 100% of U.S. EV and ESS battery deployment needs under the two scenarios. The purpose of this analysis is to evaluate how U.S. material demands may be fulfilled by domestic supply, including both mining and recycling, and complemented by international sources.

ANL-High projects that 2023 demand for lithium will increase by 16x, nickel by 13x, cobalt by 9x, and manganese by 46x in 2035. ANL-Low projects 2023 demand for lithium to increase by 10x, nickel by 8x, cobalt by 6x, manganese by 25x in 2035. Significant growth in the demand for these materials underscores the importance of strategies to grow supply chains.

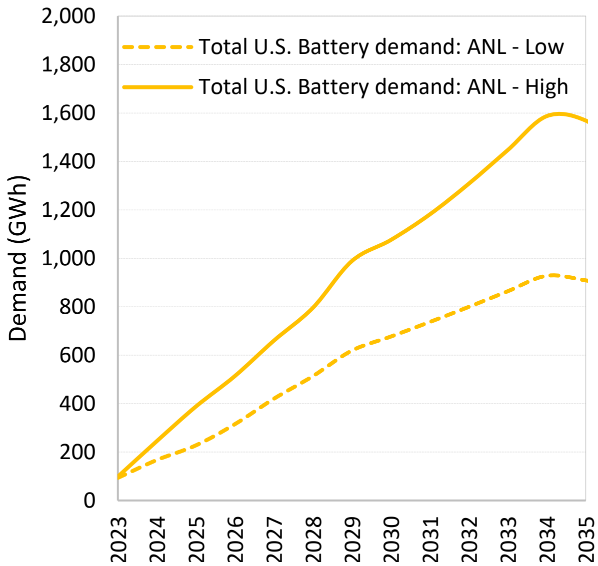

Figure 16. Battery demand.

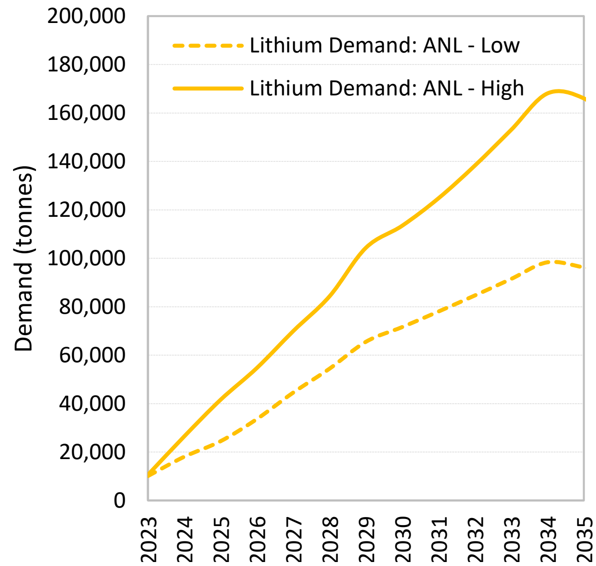

Figure 17. Lithium demand.

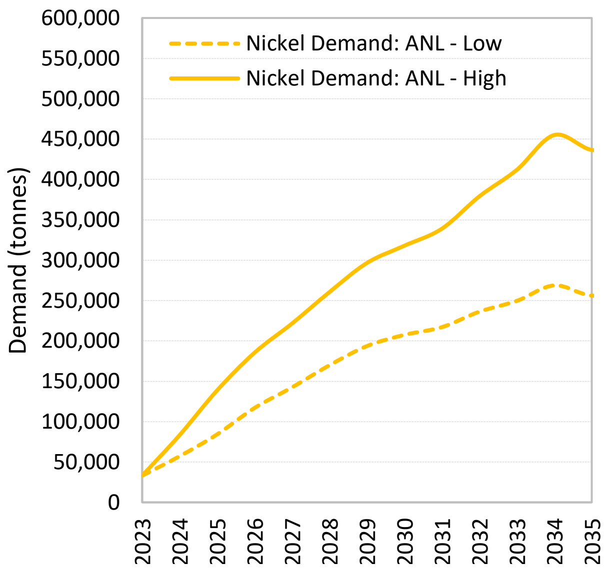

Figure 18. Nickel demand.

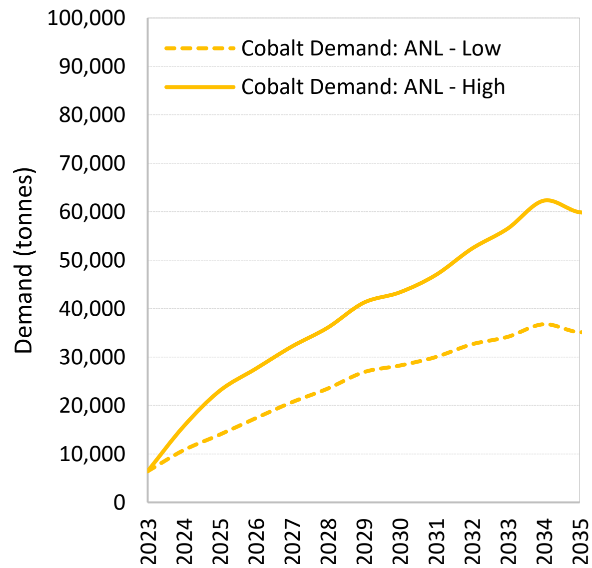

Figure 19. Cobalt demand.

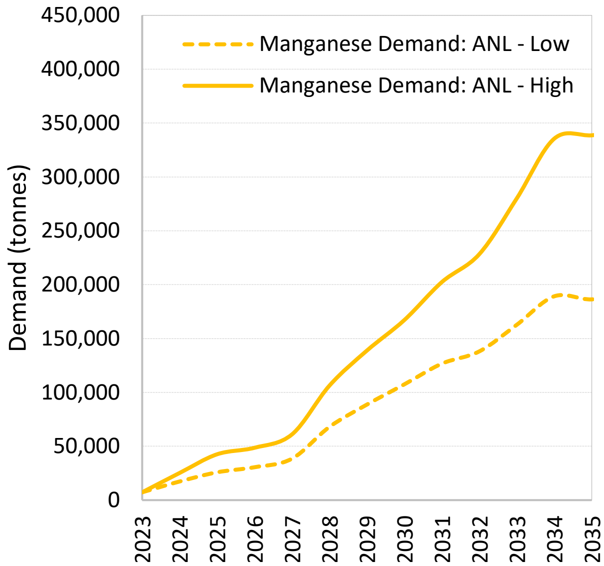

Figure 20. Manganese demand.

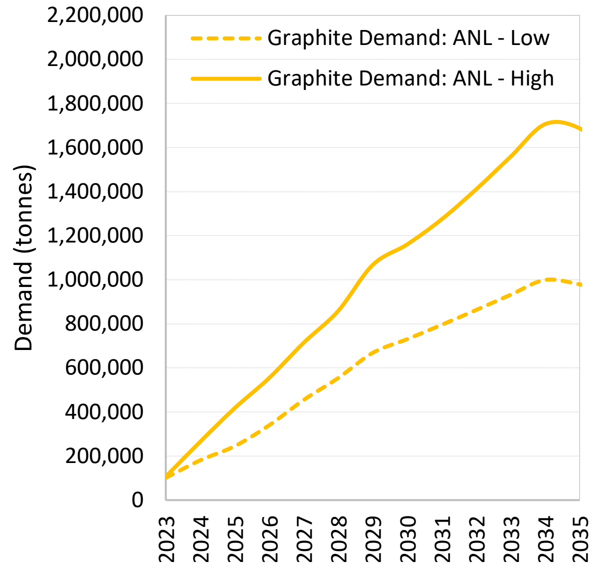

Figure 21. Graphite demand.

Electric vehicle-specific demand estimates in Figure 17 through Figure 21 are compared to those from an OnLocation study (De la Chesnaye et al., 2023) in Appendix I: Demand Projections Methodology. The sales forecasts in the OnLocation Scenario align closely with those in ANL-Low. As both studies assume that EV batteries will be lithium-ion, total GWh demand and materials demand for lithium and nickel are similar.

In contrast, the introduction of new battery chemistries in ANL's scenarios show different projections for manganese and cobalt. ANL anticipates nearly 13% share of manganese-rich batteries by 2035, whereas OnLocation excludes the market entry of Lithium Manganese Oxide (LMO) batteries beginning in 2025 due to assumptions about low specific energy. Thus, illustrating the importance of how battery chemistries affect demand trajectory, ANL estimates around 5x higher demand for manganese and 30% lower demand for cobalt demand than On Location.

IV. POTENTIAL FOR BATTERY MATERIALS RECYCLING

Given the locations of geological reserves of certain critical minerals, this section quantifies the battery materials that could be accessed by recycling in the U.S. Recycled materials entering a circular economy[76] could offset the need for newly mined materials and increase environmental benefits of EVs.

The Lithium-ion Battery Resources Assessment (LIBRA) system dynamics model (NREL, 2023) was employed, considering both demand scenarios. LIBRA tracks material flows along the battery supply chain, from the in-use phase through to EOL. Projections presented here quantify the battery minerals that could be reclaimed by recycling facilities. Toro et al., 2023 and Zheng et al., 2023 recognize existing challenges in recycling and addressing these obstacles will be pivotal in realizing potential recycling capacity.

These LIBRA projections use the distribution of battery chemistries in new EVs, as detailed in Section III, and quantify the manufacturing waste and EOL material from retired light-duty BEV and ESS batteries. While there are other sources of scrap beyond EV and ESS, including nickel in steel scrap from other industries, the analysis presumes that these recycled materials are more likely to return to their original uses rather than be integrated into the battery supply chain. The expected lifespan for LDVs is set at 15 years, while the battery lifespan for ESS is projected to start at 9 years in 2010 and then increase linearly to 15 years by 2025. The quantity of material recovered by each battery chemistry is obtained from the 2023 version of the EverBatt model (Argonne National Laboratory, 2023).

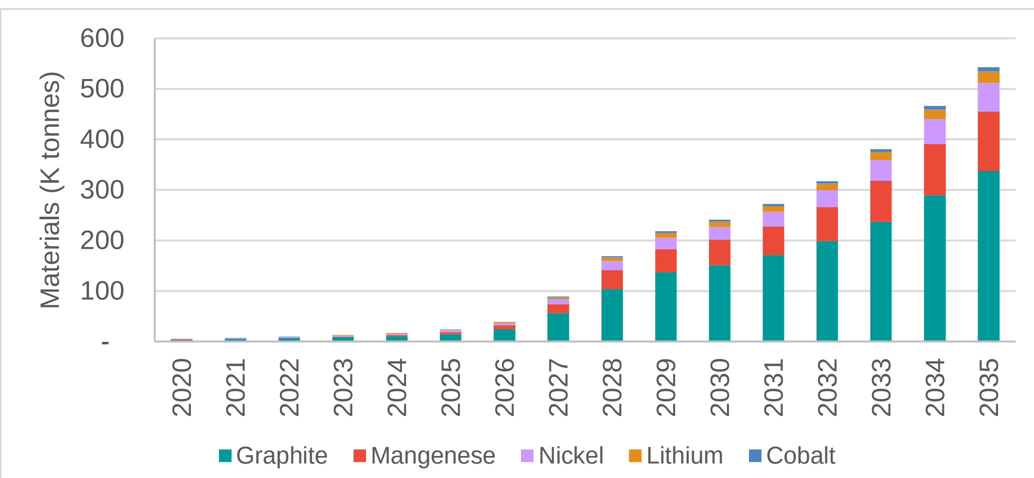

Figure 22. Total Recycling Feedstock Availability: High Scenario.
Source: NREL's LIBRA estimates.
Note: Lithium estimates are in units of contained Li metal (tonnes).

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76 Advanced Research Projects Agency for Energy. U.S. Department of Energy Announces $30 Million to Develop Technologies to Enable Circular Electric Vehicle Battery Supply Chain, January 31, 2024. Available at https://arpa-e.energy.gov/news-and-media/press-releases/us-department-energy-announces-30-million-develop-technologies-enable

Figure 22 and Figure 23 display graphite, manganese, nickel, lithium, and cobalt contained in manufacturing scrap and EOL batteries through 2035 in ANL-Low and ANL-High and underscore the potential role of recycling to supplement newly mined materials.

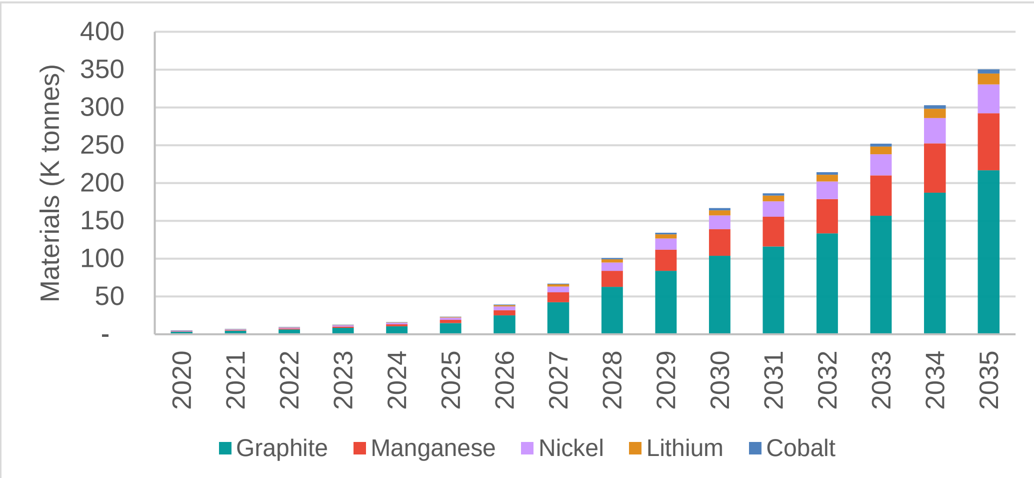

Figure 23. Total Recycling Feedstock Availability: Low Scenario.
Source: NREL's LIBRA estimates.

Of the five materials analyzed, graphite represents the largest mass of recovered material, increasing in direct proportion to demand. Manufacturing scrap, assuming a 92% battery manufacturing process yield (BNEF, 2021), contributes more recycled material than EOL batteries through 2035. A particularly steep rise in the mass available to be recycled for all materials from 2026 through 2030 reflects the steepest increase in EV demand over the same period in both scenarios. Section V through Section IX depicts growth in manufacturing scrap and EOL batteries across the five materials.

V. LITHIUM ASSESSMENT

a. Global mining supply outlook

Current known reserves and production

Global lithium mining has expanded rapidly in recent years in response to growth in battery demand. Lithium is produced primarily through evaporation of brines containing lithium, especially in Chile and elsewhere in South America, and mining of spodumene ores, largely in Australia. The distribution of lithium production and reserves by country in 2022 is shown in Table 1. Australia is the leading producer with 47% of world production, followed by Chile, China, and Argentina. Chile has the largest reserves, followed by Australia, Argentina, and China. The U.S., Canada, and Mexico, which are currently not large producers of lithium, all have significant reserves and could bolster increased production in North America. Bolivia, which possesses the largest lithium resources of any country at 112 million metric tonnes LCE, could also increase production though most of these resources are not yet classified as reserves (USGS, 2023).

Table 1. Key lithium mining countries: production and reserves

Country	2022 Production (tonnes LCE)	% of world production	2022 Reserves (thousand tonnes LCE)	% of world reserves
Australia	324,689	47%	33,001	24%
Chile	207,588	30%	49,502	36%
China	101,133	15%	10,646	8%
Argentina	33,001	5%	14,371	10%
Brazil	11,710	2%	1,331	1%
United States	6,000	1%	5,323	4%
Zimbabwe	4,258	<1%	1,650	1%
Portugal	3,194	<1%	319	<1%
Canada	2,661	<1%	4,950	4%
Mexico	0	0%	5,554	4%

Sources: USGS, S&P Global.

Annual production projected through 2035

Figure 24 projects growth in mine production by country through 2035. Details on the methodology are included in Appendix II: Supply Projection Methodology. Projections show a rapid projected increase in world lithium production. The U.S. could also become the largest lithium producer in the world by 2035 if all planned projects proceed to production on schedule. A more detailed examination of domestic mining projects and the challenges they face is presented in the next section. Argentina, Canada, Mali, and the Democratic Republic of Congo are also expected to increase their share of world production, while Chile's share is projected to decline as other producers ramp up. Direct lithium extraction from brines could also increase production capacity of existing brine sources such as those in Chile, Argentina, and the U.S., which is not accounted for in the S&P data (Goldman Sachs, 2023).

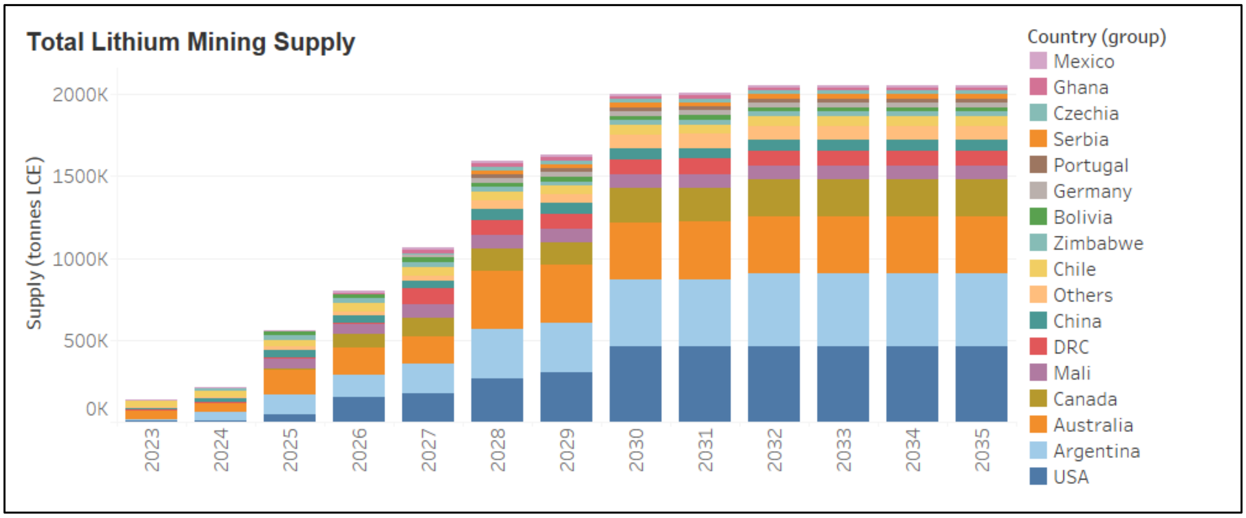

Figure 24. Global lithium mining supply outlook.

Source: ANL estimates based on data from USGS, S&P Global, company investor reports, technical reports, press releases, and news journals.

Note: Data for domestic project last updated February 2024, for international projects September 2023.

Reserves, exploration projects and projected production all indicate which countries could emerge as key future players in the lithium market. The U.S., Argentina and Canada are particularly well positioned to expand their role in lithium markets, Bolivia has the potential to become a top producer if its vast lithium resources are tapped, and Mexico also has sufficient reserves to increase its production if these reserves are developed. Australia is also likely to continue expanding its already large role as a top producer of lithium. If U.S. lithium extraction realizes current projections, domestic supplies may meet a significant portion of U.S. demand and would well complement supplies from allies in Australia and across the Americas.

b. Domestic mining supply outlook

A significant transformation of the U.S. lithium supply chain is underway. With lithium supply expected to more than double by 2025, the U.S. is poised to become a key global player by 2030.

Table 2. Example of domestic lithium projects

Property name	Development stage	Anticipated annual capacity (tonnes LCE)	State	Projected start date [a]	Data Source
Paradox	Feasibility Complete	13,074	Utah	2025	Anson Resources
Silver Peak	Operational	5,000	Nevada	Active	Steven, 2022
South-West Arkansas	Prefeasibility complete	26,400	Arkansas	2027	Standard Lithium
Fort Cady	Under Construction	4,990	California	2026	5E Advanced Materials
Clayton Valley (Zeus)	Preliminary assessment/Prefeasibility	31,900	Nevada	2030	Noram Lithium Corp
Round Top	Preliminary assessment/Prefeasibility	9,800	Texas	2030	Texas Mineral Resource Corp
Clayton Valley	Feasibility Started	27,400	Nevada	2028	Century Lithium
Thacker Pass (Phase I)	Under Construction	40,000	Nevada	2026	Lithium Americas
Thacker Pass (Phase II)	Construction Planned	80,000	Nevada	2029	Lithium Americas
Piedmont	Feasibility Complete	26,400	North Carolina	2025	Piedmont Lithium
Rhyolite Ridge	Construction Planned	20,600	Nevada	2026	Ioneer
TLC Phase I	Prefeasibility	24,000	Nevada	2028	American Lithium
ABTC	Construction Planned	26,400	Nevada	2026	American Battery Technology Company
Kings Mountain	Under Construction	50,000	North Carolina	2026	Albemarle

[a] The start dates for the projects are adopted as provided through press releases or company investor reports. In cases where an anticipated start date is not specified, ANL provides an estimated start date. This estimate is based on assumptions about the typical timeline for project initiation, provided all necessary elements align as anticipated. It is important to note that any failure in meeting necessary prerequisites such as technical requirements, sustaining project economics, permitting, or financing could result in project delays or, in extreme cases, even cancellation. Thus, actual start dates could be earlier or later than reported here.

Note: The data was last updated in February 2024. The list only includes projects with publicly available information and is intended solely for illustrative purposes. Some evaluated projects are excluded from this list.

U.S. domestic lithium expansion in Table 2 is driven by several projects currently in the pipeline, supported by the growing demand for lithium by EVs. Among these projects are Fort Cady, Thacker Pass, Rhyolite Ridge, and Kings Mountain, which are all under construction. Additionally, there are several other projects in the prefeasibility or feasibility studies phase, including ones at Salton Sea and Clayton Valley. The Salton Sea region has received attention in recent years given the large resource of lithium contained in the area's geothermal brines, a byproduct of geothermal electricity generation. Recovering lithium from geothermal brine through direct lithium extraction (DLE) can avoid many of the environmental impacts of mining while adding a major source of domestically produced lithium.[77] Three companies are currently operating or building power plants in the Salton Sea region with plans to recover lithium from geothermal brine.

Figure 25 illustrates the potential for domestic lithium production to more than quadruple by 2030, with most near-term capacity expected from Thacker Pass, Kings Mountain, Piedmont, South-West Arkansas, and Rhyolite Ridge.

[77] https://eta-publications.lbl.gov/sites/default/files/escholarship_uc_item_4x8868mf.pdf

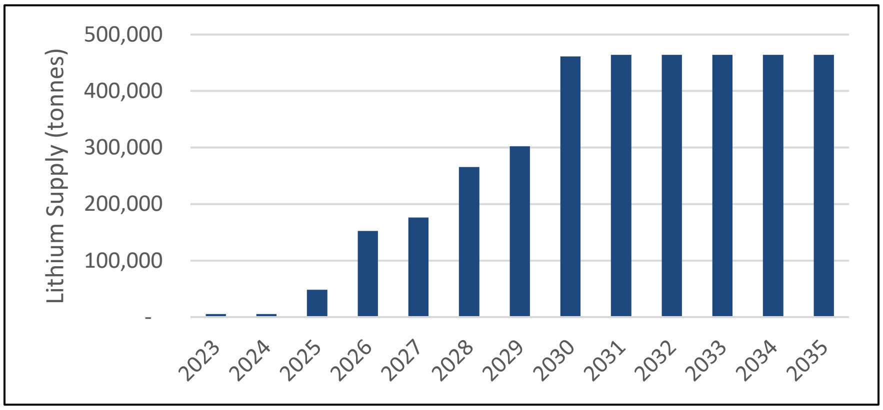

Figure 25. Prospective domestic lithium supply.
Source: ANL estimates based on data compiled from S&P Global, and company reports.
Note: Data last updated February 2024.

However, the projected capacity of these projects largely depends upon whether projects can successfully navigate all phases of development, from exploration to operation (see Table 14). A mining project's ability to reach full operation faces several risks that can lead to delay or even termination of a project. These risks include local opposition, environmental impacts, permitting issues, financing challenges, broader economic changes, and technical challenges. Domestic lithium projects are already facing challenges related to environmental impacts and local opposition. The most recent example is Compass Minerals' abandonment of its lithium brine project on the Great Salt Lake in Utah, announced in February 2024, due to regulatory risks potentially related to water.[78] Research into the most common causes of delays in the mine permitting process points to agency capacity, incomplete information, and lack of coordination.[79, 80] An overview of mine permitting delays and enabling approaches are discussed in more detail in sections X and XI.

c. U.S. supply vs. demand: A comparative analysis

This subsection compares potential U.S. lithium supply from mining and recycling in relation to meeting lithium demand needed for U.S. deployment targets for lithium-ion batteries for both EV and ES. The analysis considers high and low demand scenarios described in Section III.

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78 https://www.standard.net/news/environment/2024/feb/08/compass-minerals-to-abandon-lithium-extraction-on-great-salt-lake/

79 https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4390921

80 https://www.gao.gov/products/gao-16-165

Potential for domestic mining supply vs. demand

In the near-term across both demand scenarios, non-U.S. sources will be needed to meet U.S. lithium demand (See Figure 26). Under the low demand scenario, U.S. domestic mined lithium supply may be sufficient to meet lithium demand for the entire U.S. battery demand from 2030 to 2032. However, from 2033 onwards, demand may slightly outpace the potential domestic mined supply, though recycling may provide enough domestic lithium to meet demand through 2035. In the near term, non-U.S. sources will likely be needed to meet lithium demand needed for the U.S. deployment target. This low demand scenario for lithium aligns closely with other projections, such as those made by OnLocation.

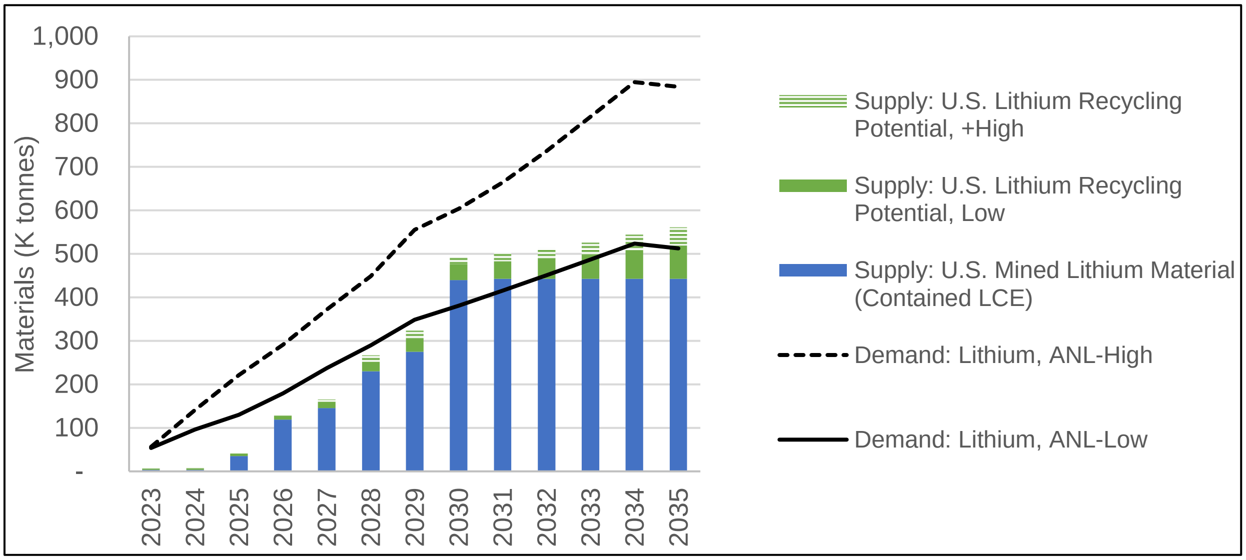

Figure 26. Potential U.S supply in meeting 100% U.S. battery capacity.
Source: ANL estimates, domestic mining supply is based on data compiled from S&P Global, company reports, and new articles.
Note: Data last updated February 2024.

Potential for domestic recycling vs. demand

While domestic lithium mining capacity is expected to be substantial, accounting for lithium recycling helps quantify replacement capacity if some domestic mining projects do not materialize. In the near term, even with recycling initiatives, non-U.S. sources are likely to be needed to lithium demand for U.S battery demand (See Figure 26).

By 2035, recycled lithium is projected at 76K to 120K tonnes LCE from both EOL batteries and manufacturing scrap (See Figure 27).

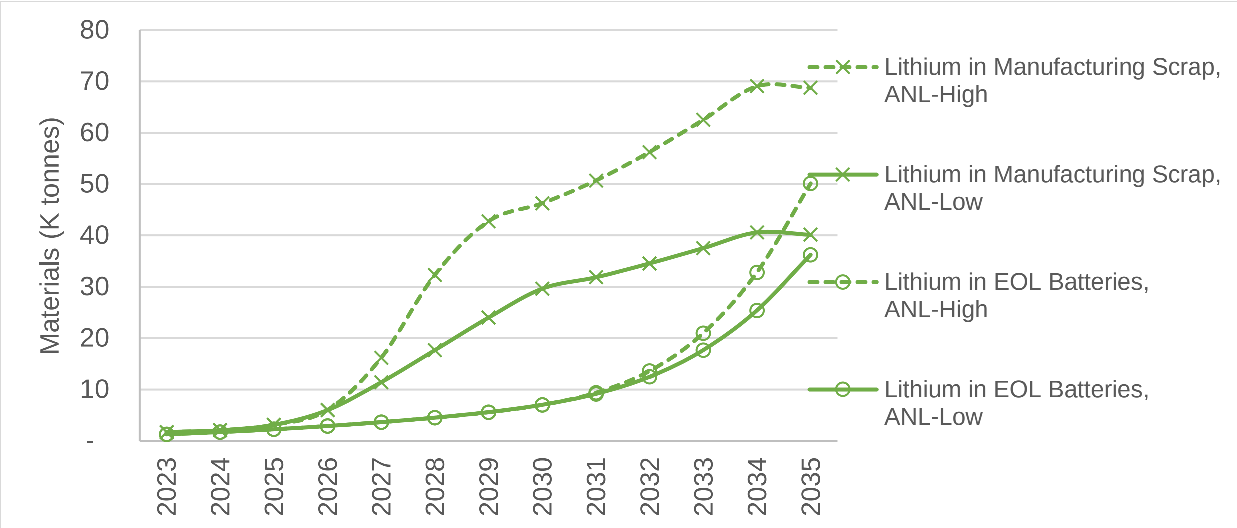

Figure 27. Potential lithium from EOL batteries and scrap.
Source: NREL's LIBRA estimates.

The quantity of lithium available from EOL batteries are the same until 2032, when a larger number of vehicles begin reaching EOL. By 2035, the lithium in EOL batteries is slightly less than the amount in manufacturing scrap in ANL-Low. In ANL-High, scrap contributes significantly more material to the recycling feedstock sooner than EOL batteries due to the surge in new EV demand.

d. The role of international trade in securing U.S. Critical mineral supply

Figure 28 indicates that in the near and medium term, a substantial portion of non-U.S. lithium production exists in FTA countries and Non-FTA countries. By 2030, several FTA and MSP partners, such as Canada, Germany, Portugal, and the Czech Republic are expected to add capacity. This expanding capacity among trade partners and allies underscores the importance of international trade in securing critical materials.

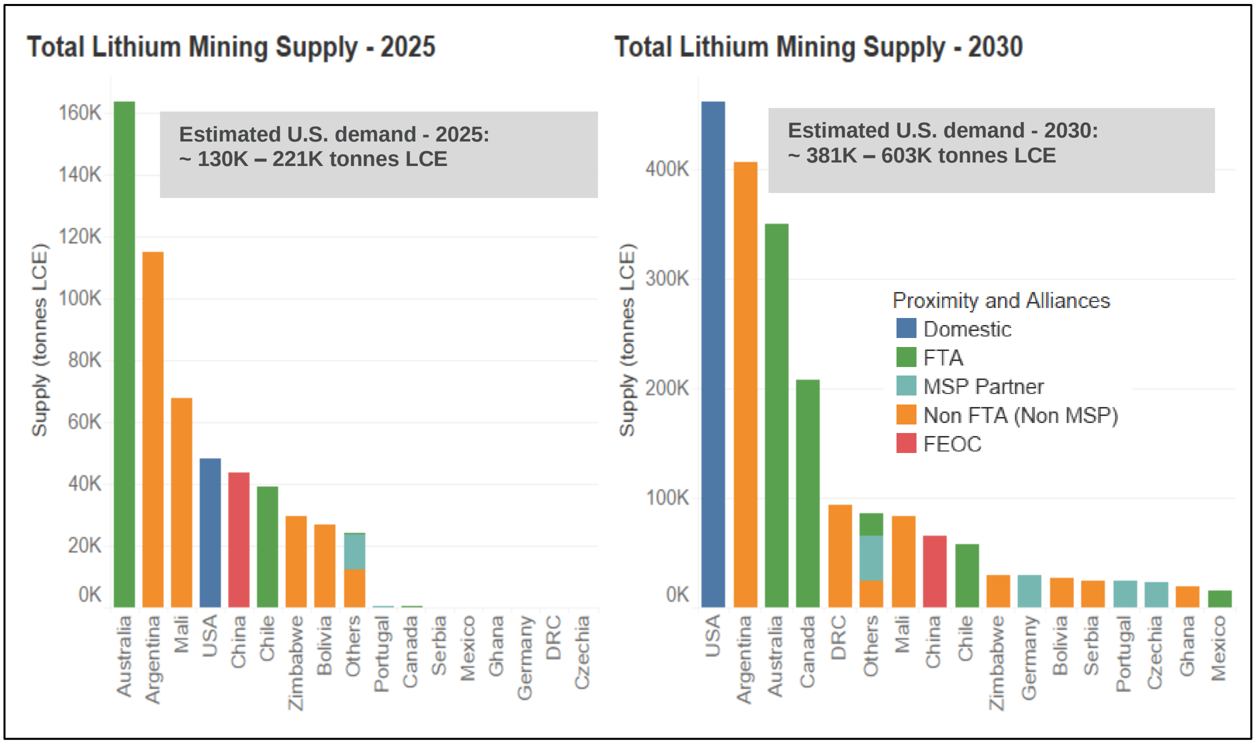

Figure 28. Lithium mining supply vs. proximity and alliances.

Source: ANL estimates based on data compiled from USGS, S&P Global, and company reports.

Note: Data for domestic projects last updated February 2024, for international projects September 2023.

VI. NICKEL ASSESSMENT

a. Global mining supply outlook

Current known reserves and production

Historically, nickel has been primarily mined for its application in stainless steel production. However, the anticipated surge in nickel demand for batteries has sparked a renewed interest in nickel mining. Nickel production is categorized as either high-grade Class I nickel, which is essential for batteries, and lower-grade Class II nickel, which has been increasingly utilized as a cost-effective alternative to Class I nickel in stainless steel production.[81]

Table 3 lists leading producers of all types of nickel in 2022 including Indonesia, the Philippines, Russia, New Caledonia, Australia, and Canada. Indonesia accounted for 49% of total production. The most substantial reserves of nickel are in Indonesia, Australia, and Brazil. Among these countries, the U.S. has FTAs with Australia and Canada.

Table 3. Key nickel producer production and reserves

Country	2022 Production (thousand tonnes Ni)	% of world production	2022 Reserves (thousand tonnes Ni)	% of world reserves
Indonesia	1600	49%	21,000	21%
Philippines	330	10%	4,800	5%
Russia	220	7%	7,500	7%
New Caledonia	190	6%	7,100	7%
Australia	160	5%	21,000	21%
Canada	130	4%	2,200	2%
China	110	3%	2,100	2%
Brazil	83	3%	16,000	16%
USA	18	1%	370	<1%

Source: USGS, 2023.

Annual production projected through 2035

Figure 29 projects growth in nickel mining using the same methodology as for lithium, detailed in Appendix II: Supply Projection Methodology. Mined nickel is projected to grow as new projects are brought online, though not as rapidly as lithium. Australia and Canada are expected to see the largest increase in their production, but with Indonesia remaining as the largest global producer of nickel.

Figure 29 also includes projections of the portion of mined nickel that is likely to be processed into Class I, battery-grade nickel. Sulfide ores are easier to process into Class I nickel

81 https://www.mckinsey.com/industries/metals-and-mining/our-insights/the-future-of-nickel-a-class-act

than laterite ores, and as a result, sulfides are predominantly used for battery-grade nickel, while laterites are used more for Class II nickel production. However, in some countries such as Indonesia and the Philippines, producers have invested in processing laterite ores into Class I nickel using technologies such as high-pressure acid leaching (HPAL)[82], supported largely by investment from China.[83] This analysis evaluates the primary mineral type of deposits in each country, and assigns its production to Class I, Class II, or a mix depending on whether most production is from sulfides or laterites, and on country efforts to process laterites into Class I nickel. Because of its efforts to process laterites into Class I nickel, Indonesia is likely to become the world's largest producer of battery-grade nickel in the foreseeable future.

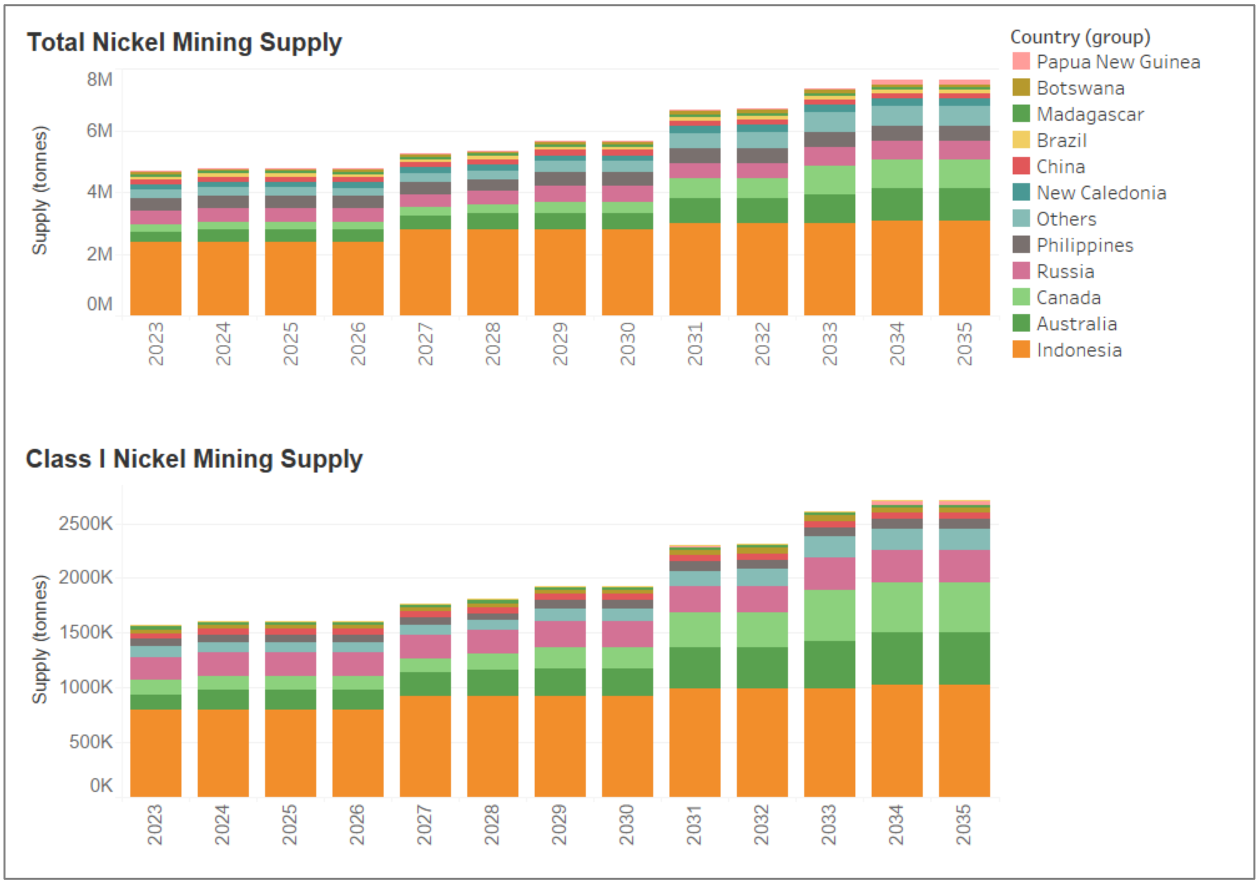

Figure 29. Global nickel mining supply outlook.

Source. ANL estimates based on data from USGS, S&P Global, company investor reports, technical reports, press releases, and news journals.

Reserves, exploration initiatives, and projected production collectively provide insights into potential future leaders in the nickel market. Indonesia, currently the leading nickel producer, is expected to maintain its top position and could potentially enhance its role in producing battery-

82 https://www.spglobal.com/commodityinsights/en/market-insights/blogs/metals/030321-nickel-hpal-technology-ev-batteries-emissions-environment-mining

83 https://carnegieendowment.org/files/Tritto_Indonesia_Nickel.pdf

grade nickel. Countries like Australia and Canada have numerous active development and exploration projects in progress, including advanced projects that could result in increased production over the next decade. Brazil, with its substantial nickel reserves, also holds the potential to boost its production. Partnerships with these countries could assist the U.S. in securing its nickel supply chain.

b. Domestic mining supply outlook

The U.S. has limited domestic production of nickel, and the capacity is not likely to change in the near and medium term. Currently, none of the production is processed domestically as battery grade nickel (Class I Nickel). Currently there are two operational domestic nickel mining projects, one in Michigan, Eagle Mine, and another in Missouri, Madison, that produces nickel from historic mine tailings (See Table 4). For years U.S. nickel production has been exported as concentrate outside the U.S. including Canada for processing and refining.[84] Missouri Cobalt, parent company of Madison Mine, has recently commissioned a nickel processing plant co-located near the mine.[85]

Table 4. Examples of domestic nickel projects

Project name	Development stage	Anticipated Production capacity (tonnes)	State	Projected start date [a]	Data Source
Tamarack	Prefeasibility	22,490	Minnesota	2032	ANL estimates; NS Energy
Eagle Mine	Operational	10,000-13,000	Michigan	2014	Ludin Mining
NorthMet	Construction Planned	3,600	Minnesota	2028	Mining.com
Madison	Operational	2,700	Missouri	2019	ANL estimates; Missouri Cobalt

[a] The start dates for the projects are adopted as provided through press releases or company investor reports. In cases where an anticipated start date is not specified, ANL provides an estimated start date. This estimate is based on assumptions about the typical timeline for project initiation, provided all necessary elements align as anticipated. It is important to note that any failure in meeting necessary prerequisites such as technical requirements, sustaining project economics, permitting, or financing could result in project delays or, in extreme cases, even cancellation. Thus, actual start dates could be earlier or later than reported here.

Note: The data was last updated in February 2024. The list only includes projects with publicly available information and is intended solely for illustrative purposes.

There are several U.S. policy levers that support build out of domestic processing and refining of battery materials including nickel e.g., LPO, the 48C tax credit, and the 45X tax credit funded through BIL and IRA. Leveraging $115 million in BIL funding, Talon Metals has plans to build a nickel processing plant in North Dakota to process the nickel extracted from Tamarack Mine in Minnesota. These midstream investments are likely to incentivize upstream nickel mining operations. There are three promising prospective nickel projects that have potential to come

84 https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-nickel.pdf

85 https://www.mocobalt.com/projects

online before 2035, both located in Minnesota (See Table 4). A significant amount of new nickel capacity could come from the Tamarack project; however, the project remains early in the development phase.

Figure 30 illustrates the potential domestic nickel production that could be realized based on the prospective projects through 2035. This figure shows domestic nickel production from mines will likely continue to be limited in the near and medium term. The projected additional capacity and related timelines will largely depend on projects successfully navigating the risks to reaching full operation described in Section X and Appendix II. Eagle Mine is expected to close by 2027 which explains a dip in anticipated production from 2027. NorthMet has faced setbacks related to environmental concerns; In 2023 the U.S. Army Corps of Engineers[86] revoked NorthMet wetlands permit over downstream pollution concerns, and the Minnesota Supreme Court[87] sent water quality permit back to the Minnesota Pollution Control Agency for additional work.

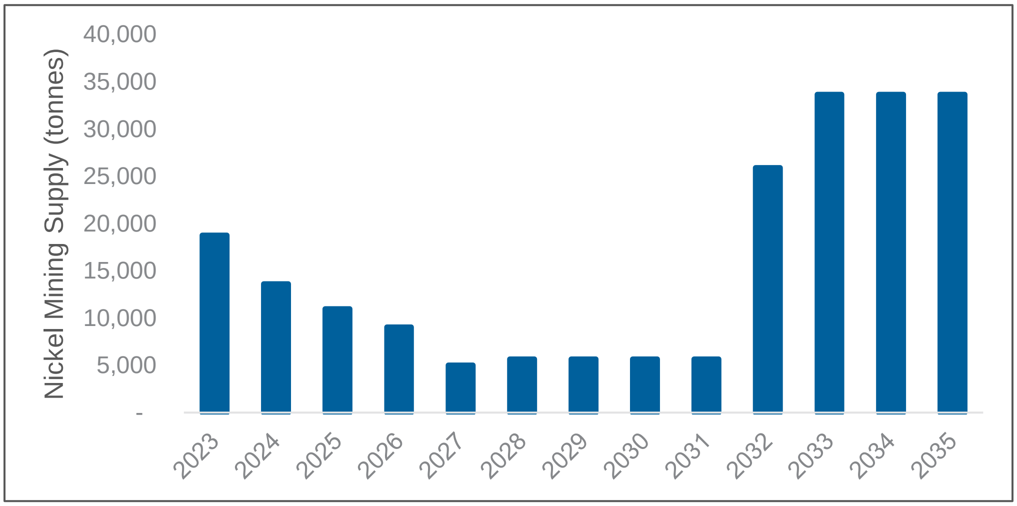

Figure 30. Prospective domestic nickel supply.
Source: ANL estimates based on data compiled from S&P Global, and company reports.
Note: Data last updated February 2024.

c. U.S supply vs. demand: A comparative analysis

This subsection compares potential U.S. nickel supply from mining and recycling in relation to meeting nickel demand needed for U.S. deployment targets for lithium-ion batteries for both EV and ES. The analysis considers high and low demand scenarios described in Section III.

86 https://www.mprnews.org/story/2023/06/06/us-army-corps-revokes-key-northmet-copper-nickel-mining-permit

87 https://www.mprnews.org/story/2023/08/02/minnesota-supreme-court-deals-another-setback-to-proposed-northmet-mine

Potential for domestic mining supply vs. demand

Contrary to lithium, the analysis indicates that the U.S. will likely not have adequate domestic capacity from both mining and recycling to support nickel demand needed for U.S deployment target for EVs and ES (See Figure 31). This deficit remains even if all potential domestic Class I Nickel mines supply is refined domestically. The demand scenario aligns closely with other projections, such as those made by OnLocation (See details in Section III).

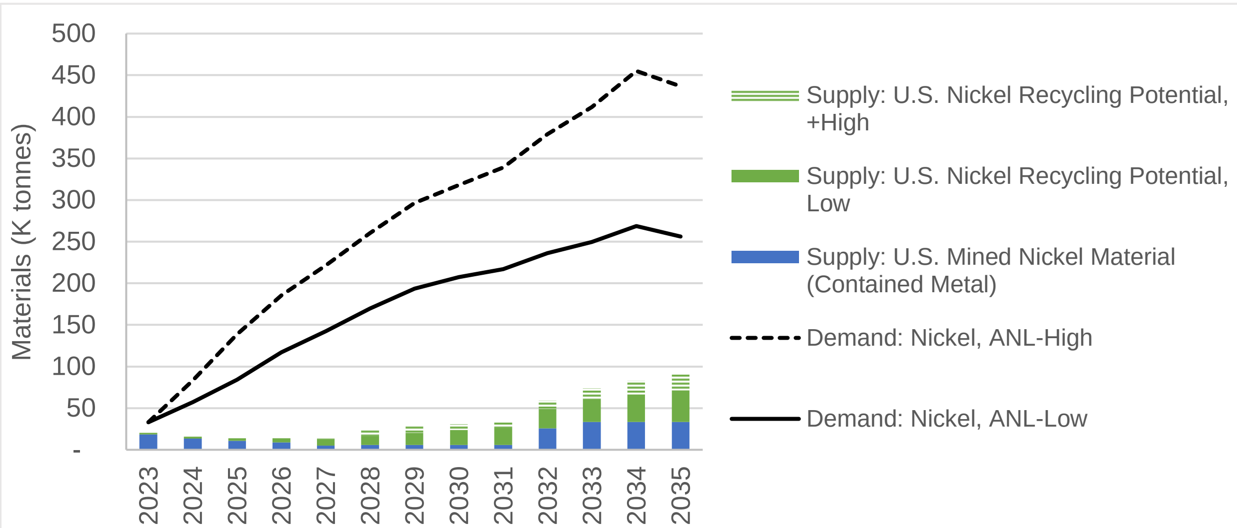

Figure 31. Potential U.S nickel supply in meeting 100% U.S. battery capacity.
Source: ANL estimates, domestic mining supply is based on data compiled from S&P Global, company reports, and new articles.
Note: Data last updated February 2024.

Potential for domestic recycling vs. demand

While recycling aids in reducing the need for newly mined minerals, a significant gap in needed nickel supply from domestic sources persists through 2035 as battery demand continues to increase (See Figure 31). By 2035, the quantity of nickel available in recycling feedstock, derived from both EOL batteries and manufacturing scrap is projected to be approximately 60,000 metric tonnes in the high scenario and 40,000 metric tonnes in the low scenario (Figure 32).

The quantity of nickel available from EOL batteries remains approximately the same between the two scenarios until 2032, when a surge of vehicles begins reaching their end of life. By 2035, the nickel in EOL batteries is nearly equivalent to the amount in manufacturing scrap in the low scenario. However, in the high scenario, scrap continues to form a larger potential contribution to the recycling feedstock than EOL batteries due to the rise in new battery demand.

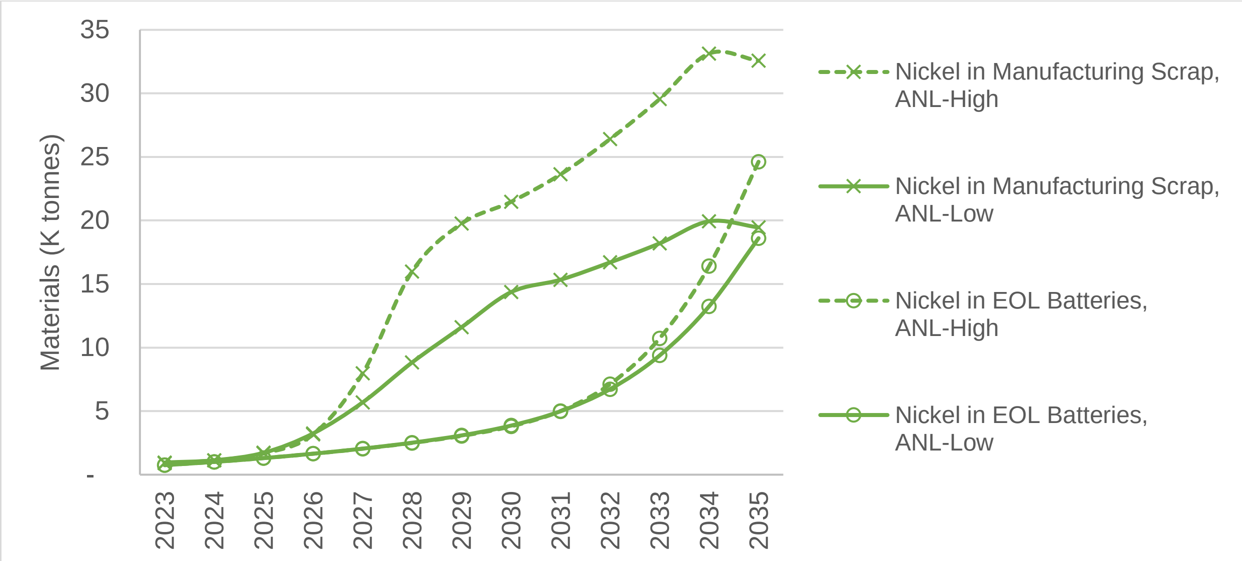

Figure 32. Potential nickel from EOL batteries and scrap.
Source: NREL's LIBRA estimates.

d. The role of international trade in securing U.S. critical mineral supply

Non-U.S. sources of nickel will remain crucial in both near and medium terms in securing supply of nickel (See Figure 33). In both near and medium term a significant portion of the nickel supply is likely to come from Non-FTA countries, particularly Indonesia. However, a few FTA and MSP partners, such as Australia, Canada, and Finland, have the potential to double their production in the medium term (See Figure 33), thereby enhancing the supply chain for nickel needed to meet U.S demand.

The supply of nickel from FTA or MSP partners may be sufficient to meet U.S. demand, potentially replacing the current supply which largely comes from Russia. However, other countries, driven by their own aggressive decarbonization objectives, also have significant demand for these resources (IEA, 2023a). Competition for resources, even among allies, could pose a challenge in meeting the demand of all partners through FTA and MSP sources. Thus, the gap in supply will likely require trade with Non-FTA countries such as Indonesia, Philippines, Botswana, South Africa, Papua New Guinea, Madagascar, Tanzania, and Zambia.

It is worth acknowledging that most of the Indonesia's nickel industry is dominated by Chinese investment.[88] However, in November 2023, the U.S. entered a Comprehensive Strategic Partnership with Indonesia, announcing the intention to partner on a roadmap to encourage the creation of a clean nickel supply chain. Concurrently, the Defense Department signed a Defense

88 https://carnegieendowment.org/2023/04/11/how-indonesia-used-chinese-industrial-investments-to-turn-nickel-into-new-gold-pub-89500

Cooperation Agreement to uphold a free and open Indo-Pacific that ensures regional stability.[89] These build upon the U.S.' support of the Just Energy Transition Partnership with Indonesia to accelerate the reduction of electricity emissions in Indonesia. The Biden Administration also announced a memorandum of understanding (MOU) between State and Indonesia's Ministry of Energy and Mineral Resources to advance technical cooperation for responsible mining and minerals processing, while supporting the development of a less-carbon-intensive critical minerals sector in Indonesia.

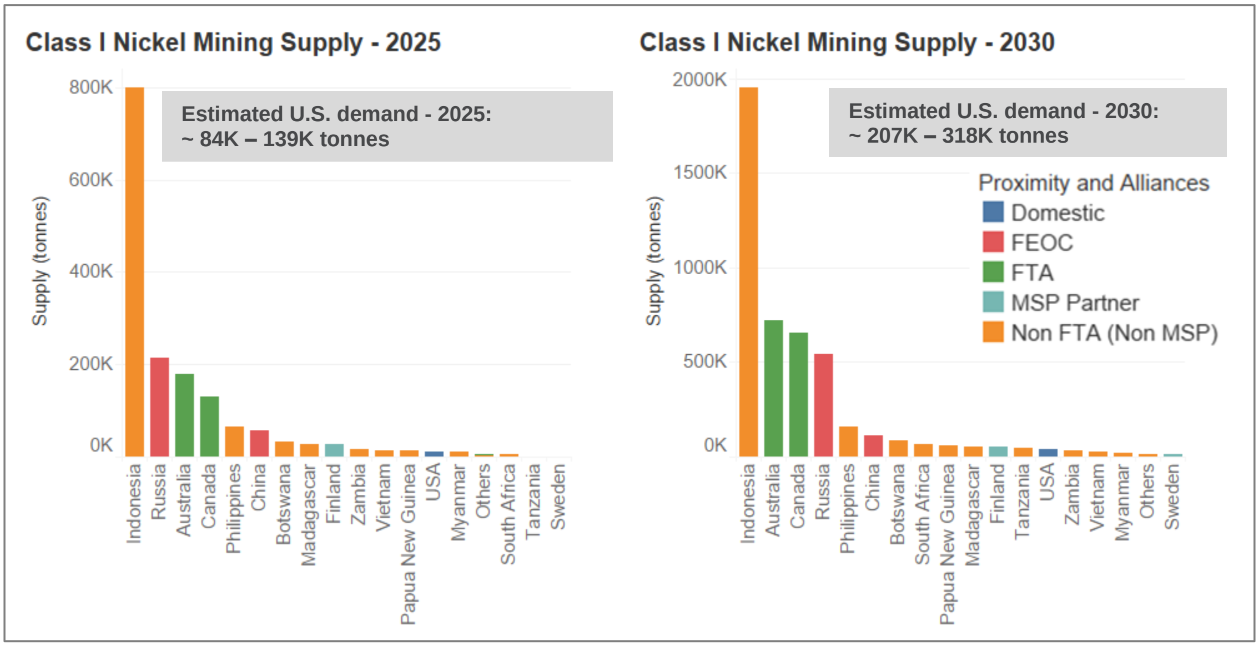

Figure 33. Nickel mining supply vs. proximity and alliances.
Source: ANL estimates based on data compiled from USGS, S&P Global, and company reports.
Note: Data for domestic projects last updated February 2024, for international projects September 2023.

As described above, the U.S. has several efforts supporting the sustainable development of nickel and cobalt resources and processing in the Philippines, including investment via USAID, DFC, and USTDA. Supporting IPEF objectives, these initiatives will also increase the production of downstream electric vehicle components and improve governance standards in the mining industry through the investments in Green Minerals Challenge.

Similarly, the U.S. has expanded support for responsible minerals development throughout southern Africa, with directed efforts to connect U.S. mining companies to developers Botswana, increase minerals transparency and governance in South Africa, Tanzania, and Zambia, and improve labor conditions in Madagascar.

89 https://id.usembassy.gov/united-states-and-indonesia-sign-defense-cooperation-arrangement/

VII. COBALT ASSESSMENT

a. Global mining supply outlook

Current known reserves and production

Cobalt has received significant attention as one of the battery minerals most at risk of disruptions to its supply (Bauer et al., 2023). Cobalt is mined largely as a byproduct of either nickel or copper mining, leading to some overlap between the supply of nickel and cobalt. Table 5 shows the top cobalt producing countries in 2022, as well as the countries that hold the most cobalt reserves. The largest producer and reserve holder is the DRC, with 70% of current world production and 48% of reserves. The concentration of cobalt mining in DRC leads to concerns regarding both vulnerabilities to supply chain disruption, and human rights impacts. Cobalt mining in DRC includes large-scale commercial mining operations, which are primarily majority-owned by China[90], as well as artisanal mining, which is done by individuals, including young children, who scrape cobalt-bearing ore from pits using hand-held tools in dangerous conditions, and sell it to intermediaries who re-sell the ore to processors.[91] Most of this cobalt is eventually processed in China.[92] Other countries that contribute significantly to global production include Indonesia, Russia, and Australia, with Australia possessing the highest level of cobalt reserves among aside from DRC (Table 5).

Table 5. Key cobalt producer production and reserves

Country	2022 Production (thousand tonnes Co)	% of world production	2022 Reserves (thousand tonnes Co)	% of world reserves
Dem. Rep. Congo	130	70%	4,000	48%
Indonesia	10	5%	600	7%
Russia	8.9	5%	250	3%
Australia	5.9	3%	1,500	18%
Canada	3.9	2%	220	3%
Cuba	3.8	2%	500	6%
Philippines	3.8	2%	260	3%
Madagascar	3.0	2%	100	1%
China	2.2	1%	140	2%

Source: USGS, 2023.

90 https://e360.yale.edu/features/siddharth-kara-cobalt-mining-labor-congo#:~:text=e360%3A%20China%20now%20owns%20most,2016%20to%20a%20Chinese%20company.

91 https://e360.yale.edu/features/siddharth-kara-cobalt-mining-labor-congo#:~:text=e360%3A%20China%20now%20owns%20most,2016%20to%20a%20Chinese%20company.

92 https://www.reuters.com/markets/commodities/is-it-time-embrace-congos-artisanal-cobalt-miners-2023-04-04/

Annual production projected through 2035

Figure 34 projects growth in cobalt mining using the methodology detailed in Appendix II: Supply Projection Methodology. While DRC is projected to remain the dominant producer of cobalt, countries such as Indonesia and Australia are expected to increase their market share. It is worth noting that China has substantial presence in the DRC,[93] controlling about 50% of mining supply.[94]

Figure 34. Global cobalt mining supply outlook.

Source: ANL estimates based on data from USGS, S&P Global, company investor reports, technical reports, press releases, and news journals.

Note: Data for domestic project last updated February 2024, for international projects September 2023.

Examining reserves, exploration projects, and projected production helps to identify countries that could emerge as key future players in the cobalt market. With high levels of reserves and increased exploration activity, Australia is likely to emerge as a key alternative supplier of cobalt. Same is true for Indonesia.

b. Domestic mining supply outlook

Despite the number of cobalt projects underway domestically, cobalt production in the U.S. is likely to remain limited in the near and medium terms. Currently there are two operational domestic mining projects that produce cobalt-bearing concentrate – Eagle Mine in Michigan and Madison in Missouri.[95] There are no battery grade cobalt refineries in the country, but several efforts exist to support building-out this segment of the supply chain in the U.S., e.g., the LPO, the 48C tax credit, and the 45X tax credit funded through BIL and IRA. As noted in Section IV b.,

93 https://georgetownsecuritystudiesreview.org/2023/06/01/chinas-monopoly-over-critical-minerals/

94 https://www.instituteforenergyresearch.org/renewable/china-dominates-the-global-lithium-battery-market/

95 https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-cobalt.pdf

Missouri Cobalt is building a processing plant near Madison Mine which is likely to process cobalt as well as nickel.

Figure 35 illustrates the potential domestic cobalt production that could be realized based on the six prospective projects through 2035. This figure shows domestic cobalt production from mines will likely continue to be limited in the near and medium term.

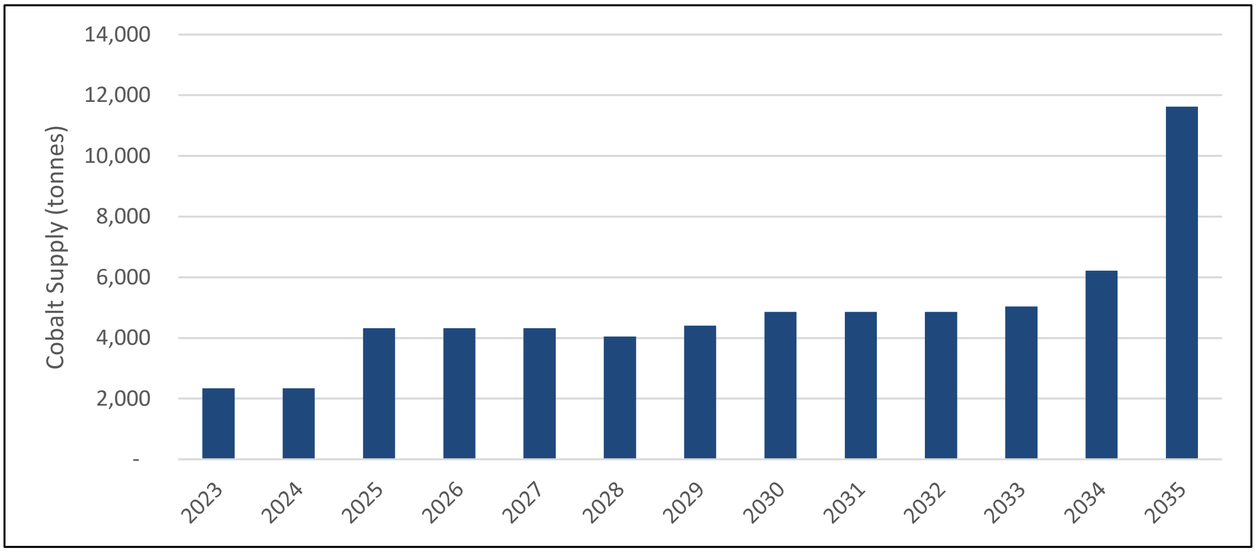

Figure 35. Prospective domestic cobalt supply.
Source: ANL estimates based on data compiled from S&P Global, and company reports.
Note: Data last updated February 2024.

There are six promising prospective cobalt projects that have potential to come online before 2035 (No public source data for cobalt projects). The projected additional capacity and the time at which the capacity enters the market will largely depend on overcoming the mining industry hurdles described earlier. Eagle Mine is expected to close by 2027 and NorthMet is under litigation as mentioned in the previous section on nickel. Given that neither of these projects contributes substantially to the cobalt supply, it is unlikely that the closure of the Eagle Mine or the potential delay in NorthMet's production will have a significant impact on the forecasted domestic production. A significant amount of cobalt capacity could come from Iron Creek project (Holley et al., 2023). However, it's important to note that this project is still in the early stages of development.[96]

96 https://electrabmc.com/wp-content/uploads/2023/03/Iron-Creek-Tech-Report-2023-Final.pdf

c. Domestic supply vs. demand: A comparative analysis

This subsection compares potential U.S. cobalt supply from mining and recycling in relation to meeting cobalt demand needed for U.S. deployment targets for lithium-ion batteries for both EV and ES. The analysis considers high and low demand scenarios described in Section III.

Potential for domestic mining supply vs. demand

Similar to nickel, the analysis indicates that the U.S. will likely not have adequate domestic mining cobalt capacity to support cobalt demand needed for U.S deployment target for EVs and ES (See Figure 36). This shortfall could potentially be addressed with domestic recycling and non-U.S. sources of cobalt (See subsequent subsections).

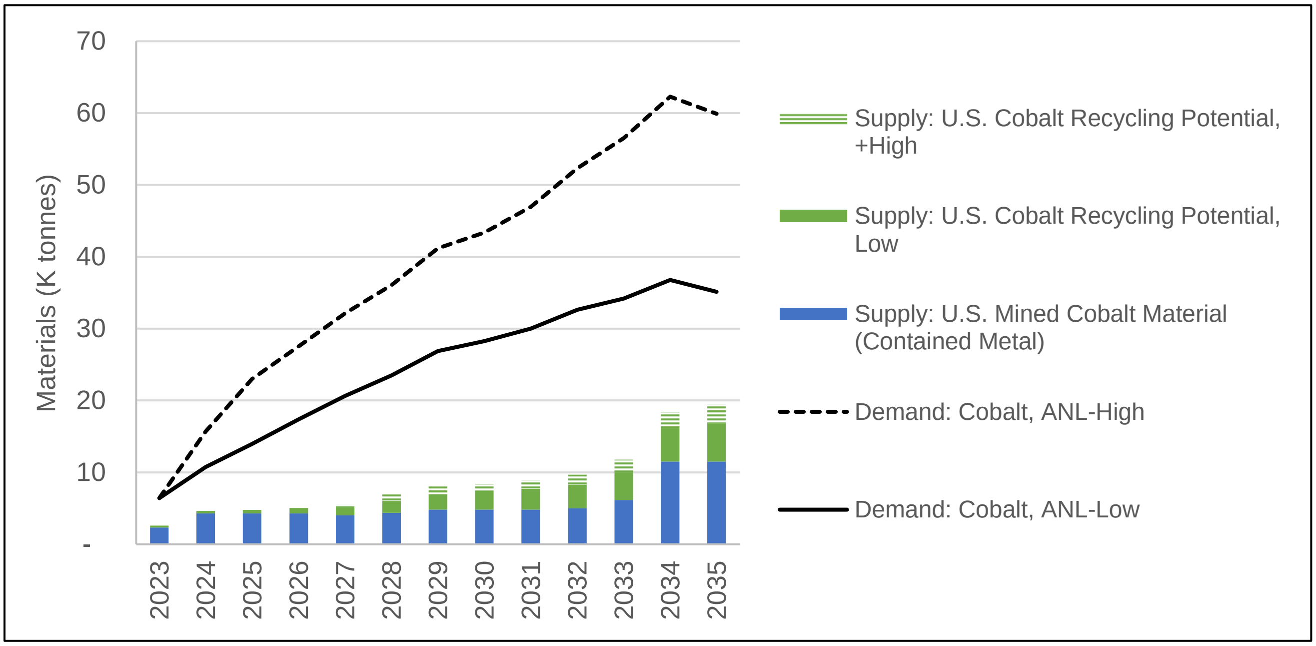

Figure 36. Potential U.S cobalt supply in meeting 100% U.S. battery capacity.
Source. ANL estimates, domestic mining supply is based on data compiled from S&P Global, company reports, and new articles.
Note: Data last updated February 2024.

Potential for domestic recycling vs. demand

Anticipating ongoing efforts to reduce the use of cobalt in lithium-ion batteries, recycling presents a significant opportunity to bolster U.S cobalt supply in the near-term and medium term. Domestic recycling initiatives could potentially reduce the domestic cobalt supply shortfall by around 8,000 tonnes in 2035. However, this supply in addition to the projected mining supply would still result in a deficit of about 40,000 tonnes of demand to be met through non-U.S. sources (See Figure 37).

By 2035, the high scenario predicts approximately 8,000 metric tonnes of cobalt available in total recycling feedstock, compared to 5,300 metric tonnes in the low scenario (See Figure 37).

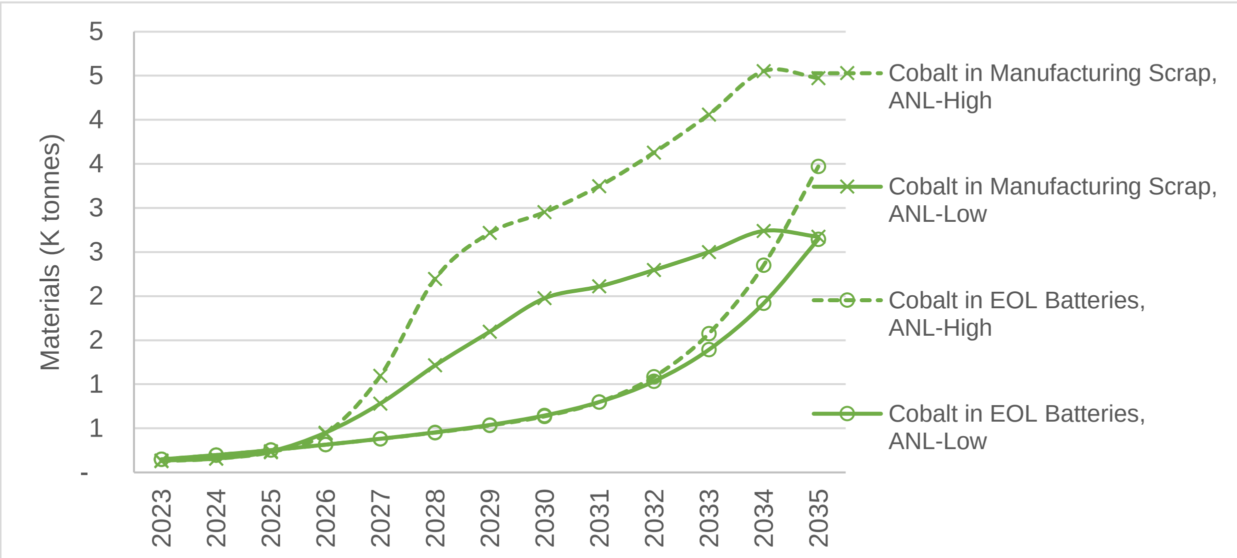

Figure 37. Potential cobalt from EOL batteries and scrap.
Source. NREL's LIBRA estimates.

The amount of cobalt available in EOL batteries remains roughly the same in both scenarios until 2032, when an influx of vehicles begins reaching their end of life. By 2035, the cobalt content in EOL batteries is projected to equal that in manufacturing scrap in the low scenario. However, in the high scenario, scrap continues to contribute more to the recycling feedstock than EOL batteries due to increased demand for new batteries. In both the low and high scenarios, supply from recycled manufacturing scrap begins to plateau or trend slightly downward. This is again as a result of the evolution of lithium-ion chemistries to cobalt alternatives.

d. The role of international trade in securing U.S. critical mineral supply

Like nickel, non-U.S. sources of cobalt will remain crucial in both near and medium terms in securing supply of cobalt. In both the near and medium terms, a significant portion of cobalt is expected to remain concentrated in Non-FTA countries, with most of the supply coming from the DRC (See Figure 38).

While the supply from FTA and MSP partners may be sufficient to meet U.S. demand for cobalt, there is likely to be increased competition for cobalt supply from FTA or MSP partners who have equally as ambitious EV and ES targets. Thus, meeting the U.S. deployment target by 2035, as depicted in Figure 38 will likely require trading with non-FTA countries such as DRC, Indonesia, Philippines, and Zambia, in addition to strengthening domestic recycling efforts. As mentioned earlier China has substantial presence in the DRC. To fully secure the cobalt supply chain, the U.S. may benefit from expanding processing and refining capacities to offer an additional trade pathway for DRC ore outside of China.

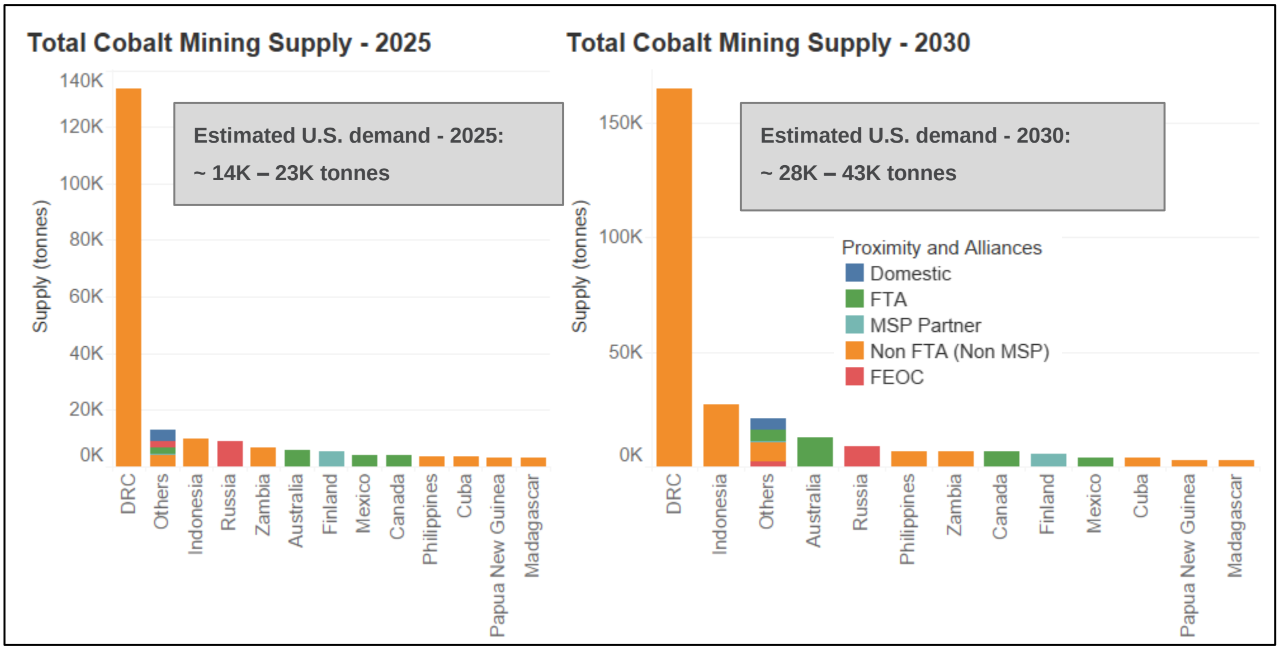

Figure 38. Cobalt mining supply vs. proximity and alliances.

Source: ANL estimates based on data compiled from USGS, S&P Global, company investor reports, technical reports, press releases, and news journals.

Note: Data for domestic projects last updated February 2024, for international projects September 2023.

Several ongoing initiatives among the U.S., Minerals Security Partners, and economic allies in the southern Africa are pursuing diversification. For example, the U.S., European Union, Japan, are collaborating with the DRC, Zambia, and Angola to finance railway infrastructure to improve efficient transport of minerals and other goods along the Lobito Corridor to maritime ports. As mentioned in the nickel assessment, the U.S. has formed regional security and economic partnerships with Indonesia and the Philippines that would co-benefit the development of cobalt resources. In addition, the Australian government is projected to increase its domestic minerals processing capabilities to reduce exports of raw materials, in response to the Clean Vehicle Credit and in support of the U.S.-Australia Alliance.[97]

97 Australian Government, 2024. Submission by the Australian Government on the Interpretation of Foreign Entity of Concern guidance by the Department of Energy – RIN 1901-ZA02 and Section 30D Excluded Entities guidance by the Department of the Treasury – RIN1545-BQ99. Comment on FR Doc # 2023-26479. January 3, 2024. https://www.regulations.gov/comment/DOE-HQ-2023-0067-0015

VIII. GRAPHITE ASSESSMENT

a. Global mining supply outlook

Current known reserves and production

Graphite has long been identified as battery material with the potential for disruption to supply due to the concentration of natural graphite mining in China (Bauer et al., 2023). This concern escalated following China's move to impose export controls on graphite in October 2023.[98] Table 6 shows the largest producers and reserve-holders of natural graphite. China dominates the market with 65% of current global production. However, their share of reserves is much lower at 16%. It is noteworthy that Turkey and Brazil possess larger reserves of natural graphite. Existence of substantial known reserves outside China indicate that there is potential for other countries to increase their share of world production.

In addition to this natural graphite production, about 58% of the world's graphite is synthetic graphite produced from low-purity hydrocarbons such as petroleum coke blended with tar pitch.[99] Top synthetic graphite producers include companies based in Japan, China, India, Germany, and the U.S.[100]

Table 6. Key natural graphite producer production and reserves

Country	2022 Production (thousand tonnes graphite)	% of world production	2022 Reserves (thousand tonnes graphite)	% of world reserves
China	850	65%	52,000	16%
Mozambique	170	13%	25,000	8%
Madagascar	110	8%	26,000	8%
Brazil	87	7%	74,000	22%
South Korea	17	1%	1,800	1%
Canada	15	1%	Unknown	Unknown
Russia	15	1%	14,000	4%
Tanzania	8	<1%	18,000	5%
Turkey	3	<1%	90,000	27%

Source: USGS, 2023.

Annual production projected through 2035

Figure 39 projects growth in graphite mining based on methodology included in Appendix II: Supply Projection Methodology. Significant growth in natural graphite production is projected outside of China, especially in Tanzania, Mozambique, and Canada. China continues to be a major

98 https://www.csis.org/analysis/chinas-new-graphite-restrictions

99 https://www.fastmarkets.com/industrial-minerals/graphite/

100 https://www.fastmarkets.com/industrial-minerals/graphite/

producer, but its production capacity remains constant, leading to a projected drop in its share of world production as new prospective projects come online from other countries. The U.S. is expected to add some production, but its share of the global market remains low.

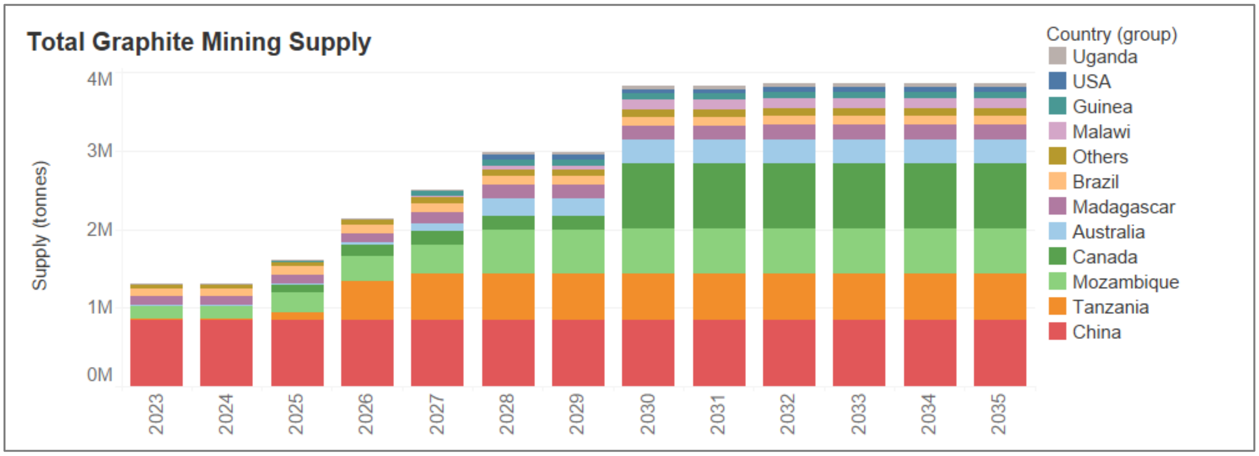

Figure 39. Global graphite mining supply outlook.

Source: ANL estimates based on data from S&P Global, USGS, company investor reports, technical reports, press releases, and news journals.

Note: Data for domestic project last updated February 2024, for international projects September 2023.

This analysis of reserves and projected production highlights several countries as potential future leaders in the natural graphite market. Canada, Tanzania, and Mozambique could challenge China's production levels, given the number and scale of advanced development projects within their territories. Canada is also actively engaged in numerous early-stage and exploration projects, in addition to their more advanced projects. Turkey and Brazil, with their ample reserves, are equally well-positioned to ramp up their production levels. Furthermore, Madagascar and Sri Lanka hold the potential to enhance their roles in the market.

b. Domestic mining supply outlook

Currently, there is no production of natural graphite in the U.S. mostly due to limited domestic resources of graphite.[101] There are currently two promising prospective natural graphite projects that are in the later development stage and likely to come online before 2035. Graphite Creek is projected to bring about 51k tonnes of annual capacity online in 2028 (See Table 7). This project has also received funding support from Department of Defense.[102]

Even though domestic natural graphite resources are limited, synthetic graphite shows promising opportunities. Unlike natural graphite, synthetic graphite is a product manufactured from petroleum coke. There has been an increasing interest in synthetic graphite from industry and

101 https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-graphite.pdf

102 https://www.defense.gov/News/Releases/Release/Article/3459556/dod-enters-agreement-to-expand-capabilities-for-domestic-graphite-mining-and-pr/

governments over the past decade in effort to diversify supply beyond China.[103] BIL and IRA have provided significant funding opportunities allocated through the LPO, grants, and tax credits that could support domestic scaling of synthetic graphite. BIL has already provided funding to five synthetic projects highlighted in Table 7. For example, Novonix was recently awarded $100 million of grant funding from BIL to bring the first synthetic graphite facility online by 2024.[22] Anovion LLC has received $117 million from BIL for their New York and Georgia synthetic graphite facilities projected to commission 2026 and 2027, respectively.

Table 7. Examples of domestic graphite projects

Project name	Development stage	Type of product	Anticipated capacity (tonnes)	State	Projected start dates [a]	Data Source
Graphite Creek	Feasibility	Natural graphite	51,813	Alaska	2028	Graphite One Inc
Anovion Plant 1	Definitive Feasibility Study	Synthetic graphite	35,000	New York	2026	DOE BIL FOA
Anovion Plant 2	Construction Planned	Synthetic graphite	40,000	Georgia	2027	Anovion Technologies
Novonix Phase 1	Under Construction	Synthetic graphite	10,000	Tennessee	2024	DOE BIL FOA
Novonix Phase 2	Definitive Feasibility Study	Synthetic graphite	30,000	Tennessee	2026	DOE BIL FOA

[a] The start dates for the projects are adopted as provided through press releases or company investor reports. In cases where an anticipated start date is not specified, ANL provides an estimated start date. This estimate is based on assumptions about the typical timeline for project initiation, provided all necessary elements align as anticipated. It is important to note that any failure in meeting necessary prerequisites such as technical requirements, sustaining project economics, permitting, or financing could result in project delays or, in extreme cases, even cancellation. Thus, actual start dates could be earlier or later than reported here.

Note: The data was last updated in February 2024. The list only includes projects with publicly available information and is intended solely for illustrative purposes.

Figure 40 illustrates the potential domestic graphite production that could be realized based on the prospective projects through 2035. This figure shows significant domestic production will likely come from synthetic graphite – a manufactured product. Manufacturing projects do not typically face the lengthy planning timelines and complexities that are common for mining projects (See Appendix II: Supply Projection Methodology, for more details). Thus, the most uncertainty around projected graphite capacity stems from the ability of the two mines to overcome feasibility, permitting and social hurdles.

It is worth noting that the likelihood of these U.S. projects commissioning on schedule has increased since the Chinese export restriction on graphite imposed in October 2023. The price of graphite[104] has been on the decline throughout 2023, impacting several projects across the world and in some instances leading to closures. Following the China export control, however, graphite prices will likely increase. The ban may also incentivize new synthetic graphite projects in the near

103 https://www.reuters.com/world/china/synthetic-graphite-ev-batteries-can-west-crack-chinas-code-2023-09-12/

104 https://source.benchmarkminerals.com/article/china-graphite-export-restrictions-could-hinder-ex-china-anode-development

and medium term as manufacturers around the world including in the U.S. look to replace their Chinese supply of graphite. [105,106]

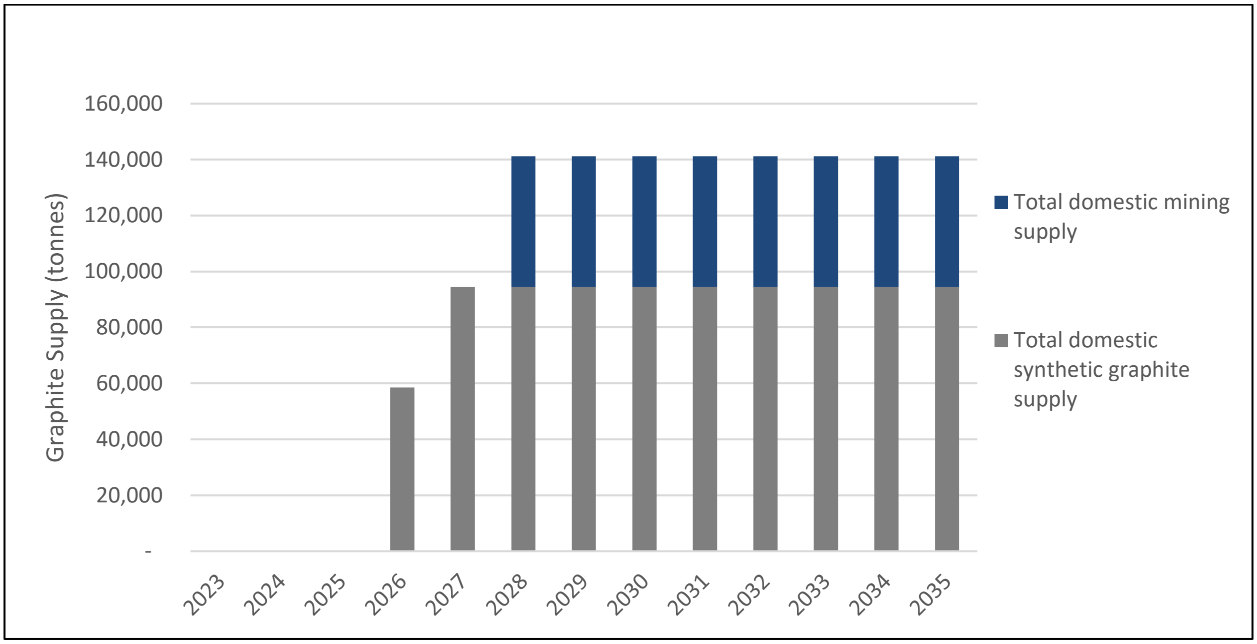

Figure 40. Prospective domestic graphite supply.
Source: ANL estimates based on data compiled from S&P Global, and company reports.
Note: Data last updated February 2024.

c. Domestic supply vs. demand: A comparative analysis

This subsection compares potential U.S. graphite supply from mining and recycling in relation to meeting graphite demand needed for U.S. deployment targets for lithium-ion batteries for both EV and ES. The analysis considers high and low demand scenarios described in Section III.

Potential for domestic mining supply vs. demand

As with nickel, the analysis shows that the U.S. will likely rely heavily on non-U.S. sources under both high and low case demand scenarios (See Figure 41) unless there are concerted efforts to expand domestic synthetic graphite production and recycling capacities. Unlike nickel, there are opportunities to expand the domestic synthetic graphite industry in the near and medium term. For

105 https://www.bloomberg.com/news/articles/2023-10-26/battery-makers-hunt-for-graphite-before-china-controls-kick-in?embedded-checkout=true

106 https://www.reuters.com/business/autos-transportation/chinas-graphite-curbs-will-accelerate-plans-around-alternatives-2023-10-20/#:~:text=Oct%2020%20(Reuters)%20%2D%20China's,industry%20executives%20and%20analysts%20said.

example, Anovion LLC who has incoming projects in New York and Georgia claims they could reach 150,000 tonnes of synthetic graphite by 2030.[107]

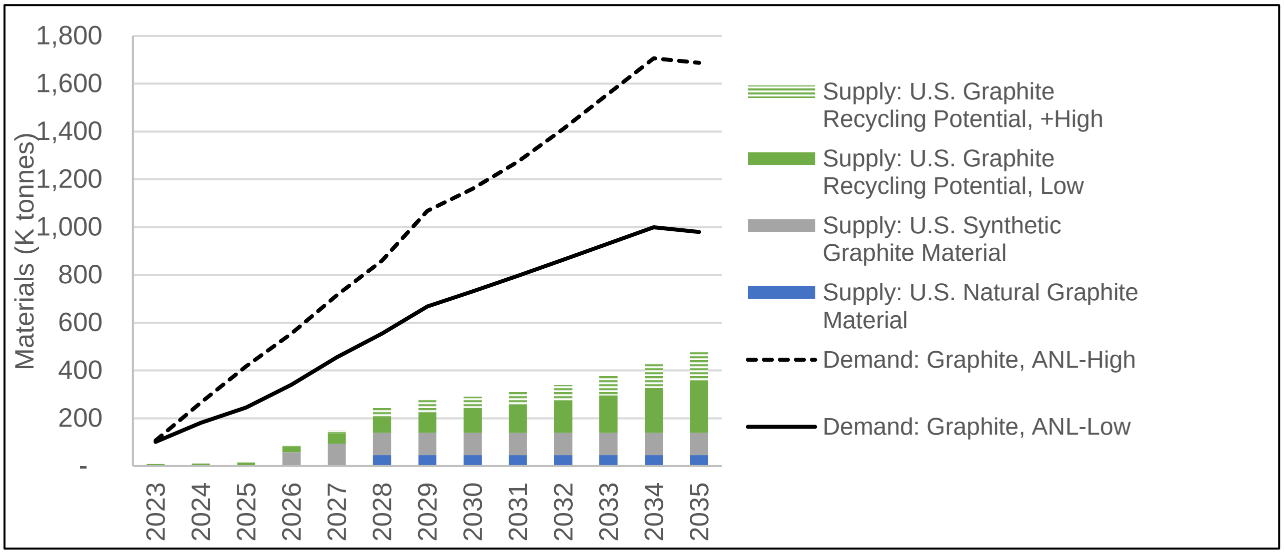

Figure 41. Potential U.S graphite supply in meeting 100% U.S. battery capacity.
Source: ANL estimates, domestic mining supply is based on data compiled from S&P Global, company reports, and new articles.
Note: Data last updated February 2024.

Potential for domestic graphite recycling vs. demand

While the recovery of high-purity graphite, which is essential for batteries, is not currently practiced, it is technically feasible.[108] Under high case scenario depicted in Figure 42, domestic recycling initiatives could potentially decrease the domestic graphite supply shortfall by approximately 338,000 tonnes by 2035. This would still leave a deficit of over 1,000,000 tonnes, which will likely need to be filled with non-U.S. sources. However, a portion of this gap could potentially be addressed with domestic synthetic graphite if more facilities are announced in the near and medium term.

By 2035, the high scenario predicts the availability of approximately 350,000 tonnes of graphite in recycling feedstock, compared to 220,000 tonnes in the low scenario. The quantity of graphite available in EOL batteries remains relatively consistent in both scenarios until 2032. This is when a significant number of vehicles are expected to reach their end of life. By 2035, the graphite content in EOL batteries is projected to equal that in manufacturing scrap in the low scenario. However, in the high scenario, scrap continues to contribute more to the recycling feedstock than EOL batteries due to the increased demand for new batteries.

It is important to note that if recycling graphite proves to be more costly than manufacturing synthetic graphite, it could disincentivize recycling. Investing in technology, leveraging EV

107 https://www.anoviontech.com/about-anovion-technologies/
108 https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-graphite.pdf

battery labeling[109] to bolster the increasing incentive for batteries using recycled materials[110] and implementing policy recommendations proposing to restrict the exports of black mass can avoid the leakage of domestic materials that would need to be reimported absent recycling capacity. All of these factors can help improve the cost-effectiveness of domestic recycling.

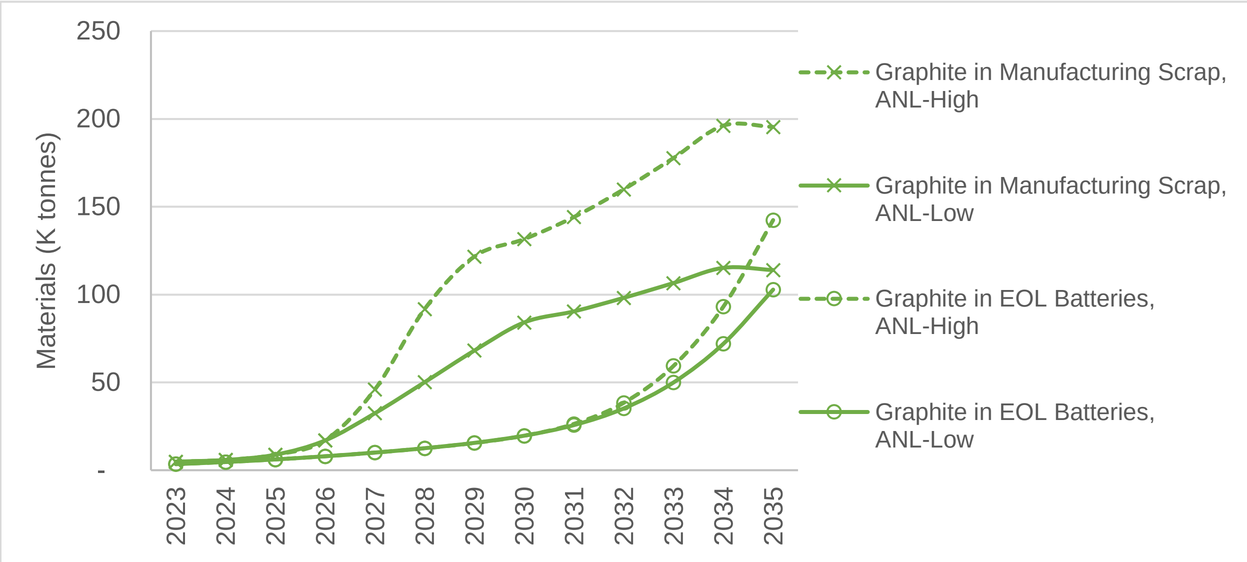

Figure 42. Potential graphite from EOL batteries and scrap.
Source: NREL's LIBRA estimates.

d. The role of international trade in securing U.S. critical material supply

International trade will likely continue to play a crucial role in securing the graphite supply chain, especially in the near term. In the near term, without accounting for potential synthetic graphite, limitations in access to Chinese supply present a challenge in meeting U.S. demand for graphite (See Figure 43). There is limited anticipated production of natural graphite in the FTA and MSP countries. In medium term, there is significant capacity that could come online in Canada and Australia (See Figure 43). However, there is potential competition for this supply, which may pose a challenge in meeting the demand of all partners in replacing the Chinese graphite.

Trade and partnership with Non-FTA countries such as Tanzania, Mozambique, Madagascar, Malawi, Brazil, Guinea, and Uganda, given their potential to increase natural graphite production capacity, will likely be crucial. For example, USAID's Green Minerals Challenge has invested in projects to increase transparency and governance of minerals extraction in Tanzania, Mozambique, Malawi, Uganda. In addition, the Development Finance Corporation (DFC) has

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109 https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/acciifro1962.6.pdf

110 I.R.C. § 30D(e)(1)(A)(ii) and I.R.C. § 30D€(1)(B) establish that to be eligible for the $3,750 critical minerals portion of the tax credit, the percentage of the value of the battery's critical minerals that are extracted or processed in the United States or a U.S. free-trade agreement partner or recycled in North America increases from 40% in 2023 to 80% in 2027 and later.

invested to expand graphite mining and processing in Mozambique.[111] Also, the U.S. has closely engaged with Australia, an FTA and MSP partner, who is developing graphite projects in Tanzania[112] and other countries responsibly.[113] Furthermore, the State Department is actively engaging with Brazil on critical minerals and sustainable economic growth as part of the Partnership for Atlantic Cooperation.[114, 115]

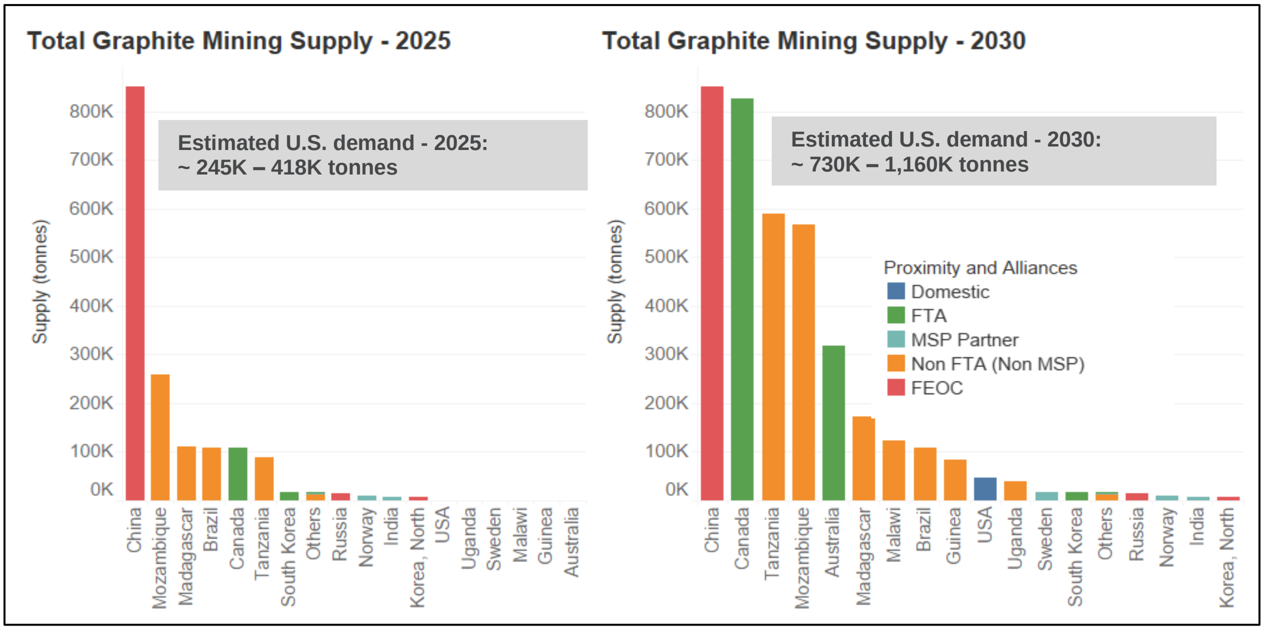

Figure 43. Graphite mining supply vs. proximity and alliances.
Source: ANL estimates based on data compiled from USGS, S&P Global, and company reports.
Note: Data for domestic project last updated February 2024, for international projects September 2023.

It is worth noting that the supply analysis outside of the U.S. solely evaluates the availability of natural graphite, excluding synthetic graphite. Given that synthetic graphite resources are not tied to local geology, this analysis may underestimate the capacity of the U.S., FTA, MSP, and other economically allied nations to meet the graphite supply required for deployment targets. The actual capacity is likely to be higher when the potential for international synthetic graphite production is accounted for. With China's export control on graphite, U.S. trade and security allied countries are likely looking to expand their synthetic graphite manufacturing capacity leveraging innovative technologies.[116] For example, in 2014 ORNL invented a

111 https://www.whitehouse.gov/briefing-room/statements-releases/2023/09/09/fact-sheet-president-biden-and-prime-minister-modi-host-leaders-on-the-partnership-for-global-infrastructure-and-investment/
112 https://www.whitehouse.gov/briefing-room/statements-releases/2023/10/25/fact-sheet-delivering-on-the-next-generation-of-innovation-and-partnership-with-australia/
113 https://www.state.gov/minerals-security-partnership-governments-engage-with-african-countries-and-issue-a-statement-on-principles-for-environmental-social-and-governance-standards/
114 https://www.voanews.com/a/blinken-meets-with-brazil-s-president-ahead-of-g20-talks/7496657.html
115 https://www.state.gov/u-s-relations-with-brazil-2/
116 https://money.usnews.com/investing/news/articles/2023-10-20/analysis-chinas-graphite-curbs-will-accelerate-plans-around-alternatives

pretreatment technique to enable the recovery of pyrolytic carbon black from tires and in 2015 licensed the process for commercial operations.[117] In 2021, the United States generated 2,185 kt of scrap tires not utilized in the market or landfilled[118] that, assuming the recovery rate from the commercial application of a derivative technology, could yield the equivalent of 417k tonnes of recycled carbon black.[119, 120] Following upon this prior work to convert waste inputs into battery grade materials, in 2021, a separate ORNL team demonstrated low-temperature electrochemical graphitization of coconut waste-derived carbon into high-quality flake graphite suitable for EV applications.[121] Recently, in New Zealand, an IPEF partner, a company announced investments to commercialize graphite derived from forest and timber byproducts and plans to enable U.S. and European production.[122] In addition, in Chile, a FTA partner, a company announced that it is engaging with investors to scale a tire-derived pyrolytic carbon and graphitization process to industrial levels.[123]

117 https://www.ornl.gov/news/rubber-meets-road-new-ornl-carbon-battery-technologies; https://www.ornl.gov/news/ornl-tires-carbon-technology-licensed-rj-lee-group

118 https://www.ustires.org/sites/default/files/21%20US%20Scrap%20Tire%20Management%20Report%20101722.pdf

119 In 2014, RJ Lee Group licensed ORNL-TT-2014-08 and in 2015 spun off the invention to Delta-Energy Group. D-E leveraged a derivative of the catalytic pyrolysis technique in a tire recycling facility in Natchez, MS that supplied carbon black to Bridgestone as its principal off-taker. https://cen.acs.org/articles/93/i16/Elusive-Dream-Tire-Recycling.html

120 https://www.bridgestoneamericas.com/en/press-release-details.en.2019.Bridgestone-Brings-First-At-Scale-Use-of-Recovered-Carbon-Black-to-Tire-Market

121 https://pubs.acs.org/doi/10.1021/acsami.0c19395; https://www.ameslab.gov/cmi/research-highlights/low-cost-graphitization-extended-to-biomass-carbon

122 https://www.carbonscape.com/latest-news/new-investors

123 https://t-phite.com/our-technology/ and https://www.cbsnews.com/news/electric-vehicle-batteries-may-have-a-new-source-material-used-tires/

IX. MANGANESE ASSESSMENT

a. Global mining supply outlook

Current known reserves and production

Manganese is mined primarily for use in iron and steel production; only a small share of mined manganese is currently used for lithium-ion batteries. Table 8 shows the top manganese producing countries in 2022, as well as the countries that hold the most manganese reserves. No one country dominates production, but the largest producer and reserve holder is South Africa, with 36% of the world's production and 37% of the world's reserves. Gabon and Australia also are major producers of manganese, and China and Brazil also have significant shares of world reserves.

Table 8. Key manganese mining country production and reserves

Country	2022 Production (thousand tonnes Mn)	% of world production	2022 Reserves (million tonnes Mn)	% of world reserves
South Africa	7200	36%	640	37%
Gabon	4600	23%	61	4%
Australia	3300	16%	270	16%
China	990	5%	280	16%
Ghana	940	5%	13	1%
India	480	2%	34	2%
Brazil	400	2%	270	16%
Ukraine	400	2%	140	8%

Source: USGS, 2023.

Annual production projected through 2035

Figure 44 projects growth in manganese mining based on methodology included in Appendix II: Supply Projection Methodology. A major expansion of production in Gabon in 2028 is projected to boost total manganese mining levels and increase the share of world production coming out of Gabon. While several new capacity additions are expected in other countries such as Australia and Namibia, they are smaller-capacity projects that are not expected to significantly increase global manganese mining capacity.

This analysis suggests that while major shifts among key manganese-producing countries are unlikely, some changes can be anticipated. Gabon, currently the second-largest producer, has the potential to surpass South Africa and become the leading manganese producer. Australia, with its ample reserves and ongoing exploration and development projects, could emerge as a significant global producer. Additionally, Brazil, China, and Indonesia hold potential to enhance their roles in manganese mining.

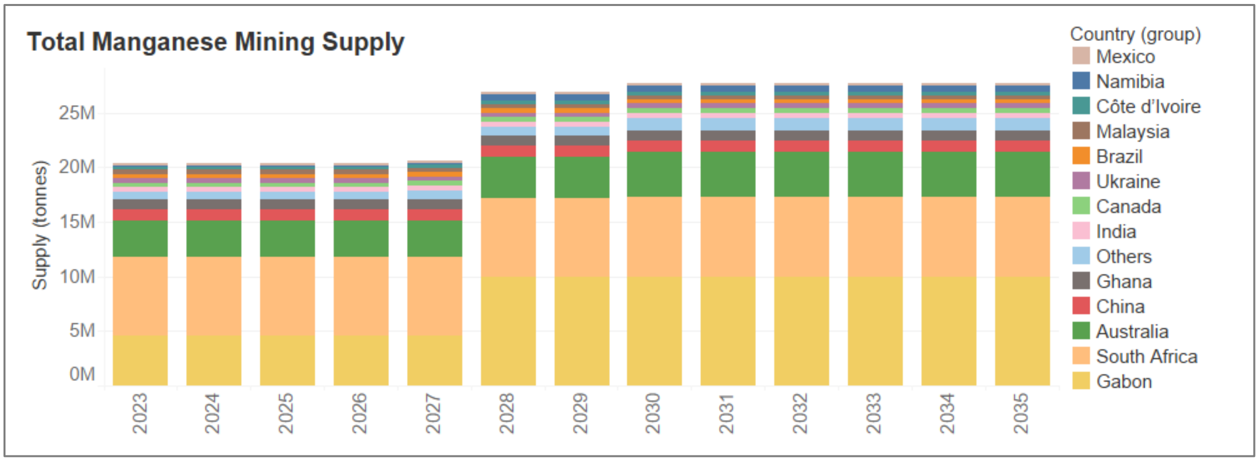

Figure 44. Global manganese mining supply outlook.

Source: ANL estimates based on data from S&P Global, USGS, company investor reports, technical reports, press releases, and news journals.

Note: Data for domestic projects last updated February 2024, for international projects September 2023.

b. Domestic mining supply outlook

Like natural graphite, there is currently no manganese mine production in the U.S. – most likely due to very low-grade quality of U.S. manganese deposits making it uncompetitive to extract.[124] There are several domestic projects in the pipeline, but they have yet to be successfully brought online. Due to insufficient information about the timelines and anticipated capacities of these projects, they were not included in this analysis.

For example, the Artillery Peak Manganese project in Arizona, completed prefeasibility study in 2011 and developed a technology to process low grade ore, yet has not started production due to economic infeasibility.[125] Hermosa[126] project in Arizona, a possible zinc – manganese – silver oxide mine, recently completed its prefeasibility study in 2023. Though the mine aims to produce high purity manganese, capacity details are unknown. The unknown tonnage of manganese could be brought online expeditiously as the Hermosa project was recently accepted into the FAST-41 program, which aims to streamline the federal permitting process.[127]

Despite of lack of mining capacity of manganese in the U.S., the 2023 DOE Critical Materials Assessment classifies manganese as being "not critical" in both the near and medium terms, due both to a lack of supply risk and overall importance to clean energy technologies.[128]

124 https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-manganese.pdf

125 https://investingnews.com/daily/resource-investing/battery-metals-investing/manganese-investing/american-manganese-inc-discusses-artillery-peak-manganese-opportunities/

126 https://www.mining-technology.com/projects/hermosa-project-arizona-usa/?cf-view

127 https://www.permits.performance.gov/fpisc-content/permitting-council-announces-first-ever-critical-minerals-mining-project-gain-fast-41

128 https://www.energy.gov/sites/default/files/2023-07/doe-critical-material-assessment_07312023.pdf

In the near and medium terms, without scaling manganese recycling, the U.S. will likely depend on non-U.S. of manganese.

c. Domestic supply vs. demand: A comparative analysis

Given the limited capacity on domestic supply mining for manganese, this subsection compares potential U.S. manganese supply from recycling in relation to meeting manganese demand needed for U.S. deployment targets for lithium-ion batteries for both EV and ESS. The analysis considers high and low demand scenarios described in Section III.

Potential for domestic manganese recycling vs. demand

With limited high-grade manganese resources in the U.S.,[129] and low likelihood of foreseeable production in the near and medium term, recycling emerges as a significant strategy for the U.S. to lessen reliance on non – U.S sources of manganese. Currently, incidental recycling of manganese from ferrous and non-ferrous scrap occurs, but the recovery rate is minimal.[129] USGS does not specify if this recycling includes the high-grade manganese required for the battery industry.

By the year 2035, high case scenario estimates suggest the presence of approximately 120,000 tonnes of manganese in recycling feedstock, as opposed to 80,000 tonnes in more conservative estimates (See Figure 45). The quantity of manganese in EOL batteries is projected to remain stable in both estimates until 2032, which marks the time when a substantial number of vehicles are likely to reach their end of life. By 2035, the manganese content in EOL batteries is expected to match that in manufacturing scrap in the conservative estimate. However, in the high case scenario estimate, scrap continues to be a larger contributor to the recycling feedstock than EOL batteries due to the heightened demand for new batteries.

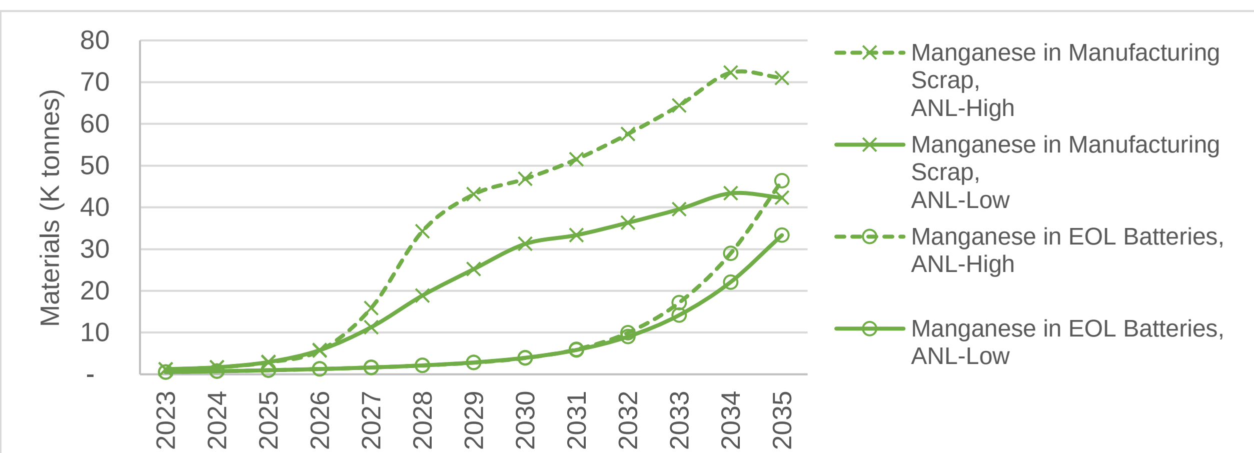

Figure 45. Potential manganese from EOL batteries and scrap.
Source: NREL's LIBRA estimates.

129 https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-manganese.pdf

Figure 46 suggests that domestic recycling initiatives could potentially reduce the domestic manganese supply gap by around 118,000 tonnes in 2035, still leaving a deficit of over 200,000 tonnes that will likely require non-U.S. sources.

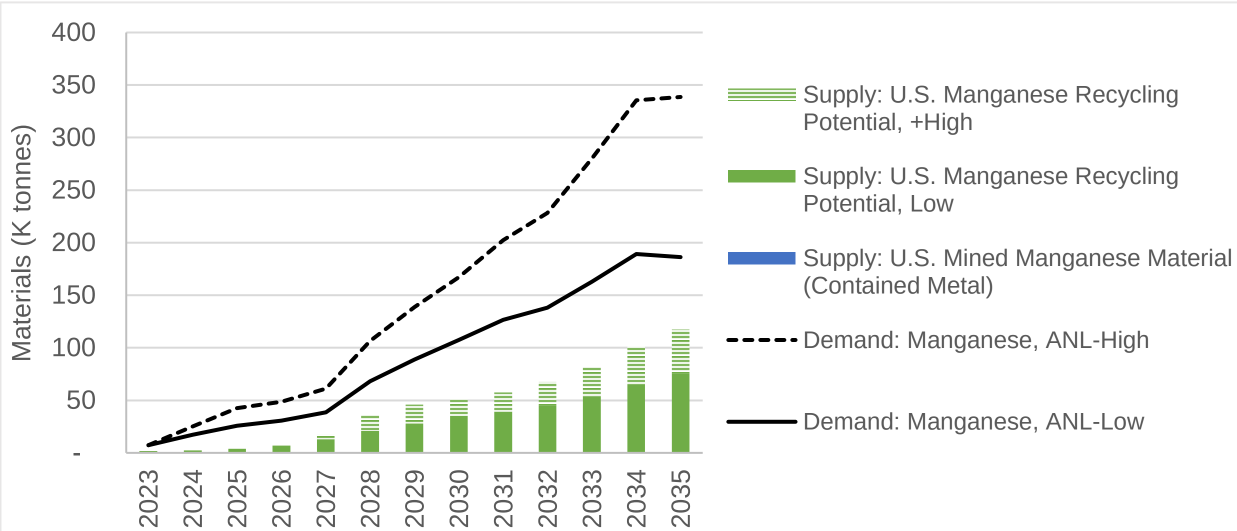

Figure 46. Potential U.S manganese supply in meeting 100% U.S. battery capacity.
Source: ANL estimates, domestic mining supply is based on data compiled from S&P Global, company reports, and new articles.
Note: Data last updated February 2024.

Even under the most conservative scenario, the anticipated domestic manganese supply shortfall persists despite recycling efforts. However, foreign dependence is considerably lessened.

d. The role of international trade in securing U.S. critical minerals supply

In the absence of recycling, the U.S. is likely to depend on non-U.S. sources for 100% of demand needed to meet its deployment target through 2035, thus international trade will likely be key. There are five companies[124] that process manganese in 6 facilities in the U.S., however, it is not clear whether the processed output can support the battery industry.

In both the near and medium terms, significant manganese reserves are concentrated among a few FTA and MSP trade partners, such as Australia, Canada, and India. Manganese supply from these countries is quite substantial and is likely to be sufficient to meet U.S. demand in both the near and medium term. This potential supply could alleviate pressures on U.S. manufacturers to replace FEOC and non-FTA supply to meet 30D tax credit requirements U.S. (see Figure 47).

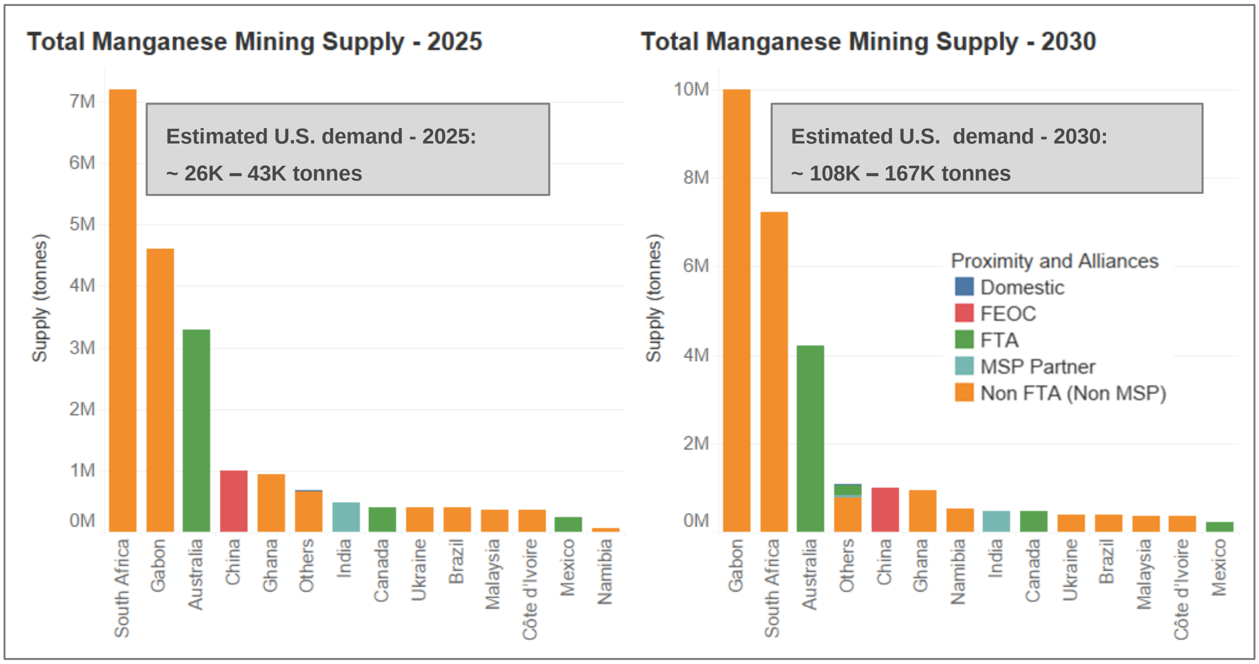

Figure 47. Manganese mining supply vs. proximity and alliances.
Source: ANL estimates based on data compiled from USGS, S&P Global, and company reports.
Note: Data for domestic projects last updated February 2024, for international projects September 2023.

X. UNCERTAINTIES

The scaling of critical minerals production is pivotal to meeting the anticipated demand for lithium-ion batteries, which are essential for achieving net-zero goals. This study suggests that both mining and recycling of these minerals will play significant roles in the near and medium-term. While the study projects a substantial capacity could come online both domestically and globally to meet the anticipated demand, several uncertainties and challenges remain that could hinder the upstream scaling of these minerals. These include environmental, geopolitical, and ethical dilemmas, maintaining economic feasibility, technical and technology challenges, and financing potential. The projections from this study do not account for these risks. This section highlights these potential risks for both mining and recycling that could reduce the anticipated availability of materials.

a. Mining Supply

Several uncertainties and challenges could potentially delay projects, cancel projects, or limit amount of minerals the U.S. can access as projected in this study.[130] Examples of these challenges could include:

- **Mineral price volatility:** Mineral prices exhibit significant volatility, and any decline in price can affect profitability of a mining project. If prices drop below the anticipated marginal cost of mine's output, it may result in project cancellation, especially if they fall below the average variable cost of mine's output. Volatility is expected for the foreseeable future,[131] which could affect the timing of mined mineral capacity entering the market.[132] Given the importance of critical minerals and recent dramatic price fluctuations, the Commodity Futures Trading Commission (CFTC) met in February 2024 to discuss and gather input on how the agency can prepare for the emergence of minerals markets, and what if any oversight role the agency may be able to play.[133] Examples of factors that usually lead to mineral price volatility include:
  - **Oversupply:** EV and ES growth has incentivized an uptick of battery mineral projects across the world. If demand cannot keep pace with supply, as new mines race to scale, there is a risk that supply could exceed demand. A potential oversupply of material could result in a drop in commodity prices, impacting profitability – especially for projects with operating costs above the prevailing market price. For example, the global nickel market had a surplus of 23,900 metric tons in September 2023, up from a surplus of 14,200 tons in the same month of the

130 https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/executive-summary

131 https://www.mckinsey.com/industries/metals-and-mining/our-insights/through-cycle-investment-in-mining

132 https://www.spglobal.com/marketintelligence/en/news-insights/research/the-big-picture-2023-outlook-for-metals-and-mining

133 https://subscriber.politicopro.com/article/eenews/2024/02/09/federal-financial-regulators-dig-into-possible-mineral-markets-00140680; CFTC's Energy and Environmental Markets Advisory Committee to Meet February 13 | CFTC

previous year.[134] Oversupply in the international market can also be a result of nations intentionally flooding the mineral market to depress prices, discouraging competition.

- **Macroeconomic conditions:** Macroeconomic conditions can weaken near-term demand expectations and depress commodity prices. A global economic slowdown presents a downside risk to the metals and mining sector, as many commodity prices slide and equity market support weakens. Over the medium term, the demand for mined commodities is expected to increase, but policy shifts, a recession, and technology disruption could weaken demand, thereby driving down the price of critical minerals.

- **Geopolitical events:** Geopolitical tensions and conflicts in commodity producing regions can disrupt supply chains and lead to fluctuations in prices. Such disruptions can cause mineral price increases by limiting material supply. For example, Indonesia, a major nickel producer, banned the export of nickel ore in 2020. This ban, while aimed at encouraging domestic processing of the mineral[135], disrupted the global nickel market. China announced export controls for graphite in 2023[136], which disrupted the global graphite market and U.S. access to graphite. These events could continue in the future for other minerals or in other countries in the pursuit of net zero emissions.

- **Rising cost:** The projection of this study did not account for potential declining ore grade quality over time for each mining project assessed. Mining is an energy intensive sector, (Igogo et al., 2021) and as ore grade of the project depletes, extraction costs are expected to rise as materials become harder to recover. Degradation of ore quality coupled with fluctuations in energy prices could result in escalating mining operational costs. This financial strain might render some mines unable to sustain operations, reducing mineral quantities that could come online.

- **Permitting issues:** Delays in or failure to obtain mining permits have significant impacts on the value of mining projects and can even lead to the cancellation of a project. As mentioned earlier, research into the most common causes of delays in the mine permitting process points to agency capacity, incomplete information, and lack of coordination.[137] Given the Biden-Harris administration's focus on securing a sustainable supply chain for minerals used in EVs, several measures have been taken to pave the way for addressing permitting issues.

  In 2022, the Biden-Harris Administration launched the Interagency Working Group on Mining Laws, Regulations, and Permitting (IWG), led by the Department of the

134 https://www.mining.com/web/global-nickel-market-sees-23900-metric-ton-surplus-in-september-insg/

135 https://www.iea.org/policies/16084-prohibition-of-the-export-of-nickel-ore

136 https://www.csis.org/analysis/chinas-new-graphite-restrictions

137 https://www.gao.gov/products/gao-16-165; https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4390921

Interior. The IWG was charged with expanding domestic mineral production with strong environmental and community engagement standards.[138]

In 2023, the IWG released its final report (IWG report), containing recommendations for reform and improvement of mining conducted on U.S. public lands.[139] The report acknowledges the limitations of the country's current mining laws and regulations, governed by the General Mining Law of 1872, and concluded its report with 65 "policy measures, regulatory changes, and legislative actions to reduce permitting timelines for exploration and development of domestic minerals on Federal land without sacrificing environmental protection."

In addition, the Federal Permitting Improvement Steering Council (FPISC) was created in 2015 to administer the FAST-41 program, which aims to improve and make more transparent the Federal review and permitting processes for certain infrastructure projects. In 2021, mining was added as an eligible sector for FAST-41. In September 2023, FPISC proposed a revision to mining regulations under FAST-41 to focus on critical minerals extraction and the whole supply chain, including refining, recycling, and beneficiation. A 2023 study concluded "that the FAST-41 process is well-situated to address common causes of delay in the mine permitting process without compromising public engagement, analytical rigor, or environmental protections."[140]

- **Increasing environmental, social, and governance (ESG) concerns:** Mining companies are under increasing pressure to address ESG in their business operations, and lacking license to operate from the communities in and around where mining companies operate is a growing risk for mining companies (Franken & Schütte, 2022).[141] The IEA writes in a recent report, "Failure to manage environmental and social impacts from minerals development will slow clean energy transitions."[142] Mining has historically caused significant environmental impacts, such as water and land resources contamination, habitat loss and degradation, and the exhaustion of water resources (Igogo et al., 2021).[143] Child or forced labor concerns have further led to scrutiny of the mining industry, especially linked to the production of cobalt in artisanal mines; while child and forced labor are unfortunately occurring in the cobalt supply chain, a USGS analysis finds that the vast majority of cobalt sourced from the DRC in 2020 was not linked to child labor.[144] Still, efforts to address labor concerns in the minerals supply chain are detailed further in the next section. In addition to labor concerns, the OECD designates the extractives industry as having the largest

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138 https://www.doi.gov/sites/doi.gov/files/biden-harris-administration-fundamental-principles-for-domestic-mining-reform.pdf

139 https://www.doi.gov/media/document/mriwg-report-final-508-pdf

140 https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4390921

141 https://www.ey.com/en_us/mining-metals/risks-opportunities

142 https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/sustainable-and-responsible-development-of-minerals

143 https://onlinelibrary.wiley.com/doi/full/10.1111/beer.12522

144 https://www.pnas.org/doi/10.1073/pnas.2212037120

percentage of foreign bribery cases of any sector.[145] Mining is also linked to loss and degradation of cultural resources.[146]

Conflicts between companies and communities related to mining increased dramatically between 2002 and 2015.[147] This has implications on supply as conflict between mining company and communities can cost a major mining project $20 million per week of delayed production due to lost sales, according to a 2014 study.[148] Opportunities for improved governance that can reduce risks related to ESG and license to operate are discussed further in section XI.

- **Financing**: The mining industry is capital-intensive and requires substantial upfront investment with minimal assurance of project realization, particularly considering the various factors previously discussed. The World Bank estimates that to support global energy transition goals, about $1.7 trillion in mineral and mining investments are required**.** [149] Despite the evident need for investment in the mining sector, high interest rates and a potential recession (or fear of) could complicate financing for some projects. The challenging financial conditions can adversely affect exploration and development activities of some mining projects. Furthermore, attracting capital to resource-rich nations that are politically unstable may pose even greater challenges due to increased perceived risks.

- **Workforce challenges:** The mining industry faces challenges related to an aging workforce and the looming retirement of experienced employees.[150] For example, in the U.S., it is projected that more than half of the current domestic mining workforce will retire by 2029.[151] This anticipated wave of retirements, coupled with low recruitment rates, presents a pressing issue for the industry. The volatility of mineral prices further complicates talent retention as job security is called into question. When mineral prices decline, the industry often resorts to layoffs, prompting workers to seek employment in other sectors. Once the talent has migrated, it becomes increasingly difficult to attract them back to the mining industry. As new mining projects ramp up, competition for the limited pool of qualified labor is likely to intensify, not only within the mining sector but also with other industries. This scenario underscores the urgent need for strategic workforce planning and talent management in the mining industry to support the anticipated ramp up.

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145 OECD, "Foreign Bribery Report," December 2, 2014, at page 8

146 https://www.doi.gov/media/document/mriwg-report-final-508-pdf

147 https://onlinelibrary.wiley.com/doi/full/10.1111/beer.12522

148 https://www.csrm.uq.edu.au/media/docs/603/Costs_of_Conflict_Davis-Franks.pdf

149 https://www.worldbank.org/en/news/feature/2022/06/06/mineral-rich-developing-countries-can-drive-a-net-zero-future

150 https://www.mining.com/mining-industry-faces-aging-workforce-and-retirement-challenges-report/

151 https://www.csis.org/analysis/united-states-needs-more-mining-engineers-solve-its-critical-mineral-challenges

b. Recycling supply

While some of the uncertainties and challenges applicable to the mining sector also apply to the recycling industry, the latter faces fewer hurdles as described in previous sections. Despite its advantages over mining, the recycling industry in the U.S. is still in its nascent stages. Consequently, technical obstacles, economic feasibility, and logistical challenges are likely to be significant hurdles in scaling up and recycling certain minerals (Gaines et al., 2018; Ma et al., 2021). Example of these challenges include:

- **Technical challenges:** Several technologies that are set to improve recycling at lower cost such as direct recycling are still under development. Recovery of certain battery materials, while technically feasible, has not yet been widely practiced. This is true for materials such as manganese and graphite. Also, battery chemistries are still evolving. As such, changes in material flows are expected to be ongoing which could present a challenge in developing standard recycling techniques and sustaining recycling facilities without expensive retrofits.[152]

- **Economic feasibility:** The economic viability of recycling certain materials could be a challenge. Initially, some materials could have higher recovery cost compared to new minerals; thus, disincentivizing recycling. For instance, the production of synthetic graphite could be more cost-effective than recycling graphite. Lowering the cost of recycling will be key in scaling and sustaining battery mineral recycling.

- **Logistics challenges:** Availability, collection, sorting of battery scrap present significant challenges. Coordinating between manufacturers and recycling facilities for manufacturing scrap material could also pose logistical difficulties and the transportation of hazardous materials could be expensive. Potential recycling policies, like extended producer responsibility, can also shift the responsibility for coordination, ownership, and cost of recycling

152 https://www.bcg.com/publications/2023/striking-gold-with-ev-battery-recycling

XI. ENABLING APPROACHES ON STRENGTHENING SUPPLY CHAINS

This section explores a range of potential enabling approaches derived from the analysis of this study that could enhance U.S. initiatives to secure the essential minerals to meet deployment of EV and ES targets.

a. Near- to medium-term approaches

- **Collaboration with trading partners**: Diversifying supply chains beyond existing FTAs could be beneficial, especially for minerals that the U.S. and its current trade partners have limited supply. This could involve strengthening trade with potential countries that have or could have significant capacity as anticipated by the analysis of this report. This could also involve joint efforts with MSP partners to ensure the success of mineral projects in member countries through coordinated financial assistance, mobilizing both government and private capital, providing technical expertise, and streamlining ESG standards to include traceability standards. The collaboration could extend to financing promising projects within non-FTA countries, given their significant capacity. This could involve leveraging existing and new interagency efforts across various agencies like State, Commerce, DOE, USAID, US DFC, USTDA and EXIM, in collaboration with the private financing sector, many of which are described elsewhere in this report.

- **Strengthening Environmental, Social, and Governance (ESG) implementation**: Improved management of social and environmental impacts can reduce risk for mining projects. Robust consultation with communities near where mining resources are located, and adherence to strong labor, human rights, and environmental practices, can reduce conflict with local communities, improve public perception on the mining sector, and facilitate project approvals.

  Internationally, some USG efforts already exist to advance ESG compliance and to improve environmental and social outcomes of minerals development: DOE's Advanced Research Projects Agency-Energy (ARPA-E) is funding 16 projects across 12 states that aim to increase mineral yield while decreasing energy and emissions from mineral extraction.[153] The U.S. Department of Labor's Comply Chain tool offers resources to companies looking to mitigate risks related to labor violations, and the U.S. Department of Labor (DOL)-funded Combatting Child Labor in the Democratic Republic of the Congo's Cobalt Industry (COTECCO) project raises awareness on child labor in the supply chain, builds monitoring and enforcement capacity, and improves private-sector monitoring and remediation of child labor violations.[154] The

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153 https://arpa-e.energy.gov/news-and-media/press-releases/us-department-energy-announces-39-million-technology-grow-domestic

154 https://www.dol.gov/agencies/ilab/comply-chain; https://www.dol.gov/agencies/ilab/combatting-child-labor-democratic-republic-congos-cobalt-industry-cotecco

DOL is also funding two four-year projects to address child and forced labor risks.[155] Through the IPEF Supply Chain Agreement, the U.S. is engaged in a Labor Right Advisory Board to promote worker rights across supply chains.[156] In November 2023, President Biden signed the "Presidential Memorandum on Advancing Worker Empowerment, Rights, and High Labor Standards Globally," directing the Secretaries of State, Labor, Energy, Treasury, Homeland Security, and Commerce, along with the Administrator of USAID and the United States Trade Representative, to address labor rights abuses across global supply chains.[157]

In complement, the U.S. Customs and Border Protection's "Green Trade Strategy" aims to coordinate environmental enforcement efforts with international partners and integrate strong environmental provisions in trade agreements. The U.S. supports the Extractive Industries Transparency Initiative (EITI) through USAID and has provided more than $24 million in support for transparency and accountability activities in countries such as Colombia, Senegal, Guyana, Ukraine, DRC, and the Philippines.[158] The U.S. has also included ESG provisions into FTAs; the U.S.-Chile FTA, for example, identified environmental projects including a project to support mining pollution remediation.[159]

- **Stockpiling and supply chain readiness**: Strategic stockpiles can serve as a buffer against disruptions and ensure access to essential materials during critical times. This approach could also protect domestic projects, both mining and recycling, from intentional oversupply by nations aimed at reducing global competition. Efforts around stockpiling are already in progress: DOD, DOE, and State executed a memorandum of agreement in early 2022 to lay the foundation for a U.S. critical minerals stockpile by creating a new interagency process for stockpiling minerals for the clean energy transition.[160] Other efforts to stabilize supply chain volatility and uncertainty could include better data tracking and sharing, alert systems, and international partnerships to respond to supply chain disruptions. A number of measures for critical minerals supply chain readiness were announced in November 2023;[161] these include a Supply Chain Agreement with IPEF, which involves Commerce-funded pilot projects to enhance supply chain resilience, and the establishment of a Crisis Response Network; a commitment with Japan and the Republic of Korea to pilot early warning systems for

155 https://www.whitehouse.gov/briefing-room/statements-releases/2023/11/27/fact-sheet-president-biden-announces-new-actions-to-strengthen-americas-supply-chains-lower-costs-for-families-and-secure-key-sectors/

156 https://www.whitehouse.gov/briefing-room/statements-releases/2023/11/27/fact-sheet-president-biden-announces-new-actions-to-strengthen-americas-supply-chains-lower-costs-for-families-and-secure-key-sectors/

157 https://www.whitehouse.gov/briefing-room/presidential-actions/2023/11/16/memorandum-on-advancing-worker-empowerment-rights-and-high-labor-standards-globally/

158 https://eiti.org/supporters/united-states

159 https://www.state.gov/key-topics-office-of-environmental-quality-and-transboundary-issues/current-trade-agreements-with-environmental-chapters/ - chile

160 https://www.energy.gov/ia/articles/us-departments-energy-state-and-defense-launch-effort-enhance-national-defense

161 https://www.whitehouse.gov/briefing-room/statements-releases/2023/11/27/fact-sheet-president-biden-announces-new-actions-to-strengthen-americas-supply-chains-lower-costs-for-families-and-secure-key-sectors/

supply chain disruptions; a DOE-developed assessment tool to assess both risk and opportunity across the battery supply chain; and prioritizing minerals supply chain resilience through the North American Leaders' Summit (NALS). The IEA announced the launch of a critical minerals security program in February 2023 to enhance security for minerals supply chains.[162]

- **Scaling recycling**: Increasing domestic recycling capacity is critical to building a resilient, secure, and sustainable supply chain for minerals. FCAB's National Blueprint for Lithium Batteries outlines several near term objectives to achieve the goal of scaling end-of-life reuse and recycling for minerals: foster the design of battery packs for ease of second use and recycling; establish successful methods for collecting, sorting, transporting, and processing recycled lithium-ion battery materials, with a focus on reducing costs; increase recovery rates of key materials such as cobalt, lithium, nickel, and graphite; develop processing technologies to reintroduce these materials into the supply chain; develop methodologies for proper sorting, testing, and balancing for second use applications; and establish federal recycling policies to promote collection, reuse, and recycling of lithium-ion batteries.[163] The DOE announced the availability of $37 million in funding to improve the economics and industrial ecosystem for battery recycling, and another $30 million to enable a circular economy for EV batteries, to be awarded in 2024.[164]

- **Workforce development**: Coordination and collaboration with academic institutions and training centers to develop the next-generation workforce to serve the potentially growing domestic mining sector and replace the aging workforce that is expected to retire in the near term. DOE, in collaboration with DOL, AFL-CIO, and other partners, launched the Battery Workforce Initiative through the National Energy Technology Laboratory (NETL) to develop training up and down the battery supply chain.[165] Talon Metals and the United Steelworkers have also announced a joint workforce development partnership for the Tamarack Nickel Project.[166] The FY24 NDAA directs that the Defense Department study the feasibility for and plan for the creation of a University Affiliated Research Center for Critical Minerals which would assess institutional capabilities and investments needed for workforce development to support needs related to critical materials.[167] The Department of Commerce, through the

162 https://www.iea.org/news/at-iea-ministerial-meeting-and-50th-anniversary-global-leaders-pledge-to-strengthen-energy-security-and-accelerate-clean-transitions-to-keep-1-5-c-target-alive and https://www.energy.gov/articles/international-energy-agency-50th-anniversary-achieves-breakthroughs-civil-nuclear-outreach

163 https://www.energy.gov/sites/default/files/2021-06/FCAB National Blueprint Lithium Batteries 0621_0.pdf

164 grants.gov/search-results-detail/351544 ; https://arpa-e.energy.gov/news-and-media/press-releases/us-department-energy-announces-30-million-develop-technologies-enable

165 https://netl.doe.gov/bwi

166 https://talonmetals.com/talon-metals-and-steelworkers-union-partner-to-advance-the-tamarack-nickel-project-for-us-ev-battery-supply-chain/

167 https://www.congress.gov/bill/118th-congress/house-bill/2670/text

CHIPS Act is funding workforce development across the battery supply chain in Missouri, New York, and Nevada.[168]

- **Improving the permitting process**: Solutions are available to the challenges surrounding permitting for critical minerals projects discussed in section X(a). Some of these solutions are outlined in the Biden-Harris Permitting Action Plan (May 2022) and subsequent implementation guidance (March 2023). The Action plan relies five key elements: (1) accelerating permitting through early cross-agency coordination to appropriately scope reviews, reduce bottlenecks, and use the expertise of sector-specific teams; (2) establishing clear timeline goals and tracking key project information to improve transparency and accountability, providing increased certainty for project sponsors and the public; (3) engaging in early and meaningful outreach and communication with Tribal Nations, States, territories, and local communities; (4)improving agency responsiveness, technical assistance, and support to navigate the environmental review and permitting process effectively and efficiently; and (5) adequately resourcing agencies and using the environmental review process to improve environmental and community outcomes.[169]

b. Medium- to long-term approaches

- **Material substitution and battery-to-battery substitution**: Replacing critical minerals with more readily available alternatives can significantly reduce dependence on specific sources. FCAB identifies cobalt- and nickel-free cathode materials; electrodes that improve energy density, safety, and cost; and revolutionary battery technologies like solid-state and Li-metal as long-term priorities. Material substitution and innovation efforts are described in more detail in section II(a).

- **Advanced recycling techniques**: While recycling holds significant potential, new technologies that have lower costs, such as direct recycling, should be commercialized and scaled. Direct recycling, which is a recycling technique that enables battery components to be reused without destroying them, is also more efficient, recovers materials of better quality and more efficiently, and has significantly less environmental impact than other battery recycling techniques (pyrometallurgy and hydrometallurgy). BIL funded research and development for advanced recycling; DOE announced more than $45 million for advanced recycling projects, including direct recycling, in November 2022.[170]

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168 https://www.eda.gov/funding/programs/regional-technology-and-innovation-hubs/2023/Nevada-Lithium-Batteries-and-Other-EV-Material-Loop; https://www.eda.gov/funding/programs/regional-technology-and-innovation-hubs/2023/New-Energy-New-York-Battery-Tech-Hub; https://www.eda.gov/sites/default/files/2023-11/Critical_Minerals_and_Materials_for_Advanced_Energy_Tech_Hub.pdf

169 https://www.whitehouse.gov/wp-content/uploads/2022/05/Biden-Harris-Permitting-Action-Plan.pdf and https://www.whitehouse.gov/wp-content/uploads/2023/03/M-23-14-Permitting-Action-Plan-Implementation-Guidance_OMB_FPISC_CEQ.pdf

170 https://www.energy.gov/sites/default/files/2022-11/Recycling and Second-Use Selections Factsheets 11-16.pdf

- **Alternative sources of critical materials**: Identifying non-traditional sources of critical materials that are available domestically, such as industrial by-products and mining waste streams, could help meet minerals demand. USG is supporting efforts to fund research into non-traditional sources of minerals: In February 2024, DOE announced it would invest $17 million into projects to recover minerals from coal-based resources, and in November 2023 USGS announced $2 million to 14 states to study critical minerals in mine waste.[171] Research suggests that resource recovery from coal and mining waste may also help remediate abandoned mines.[172]

c. Engaging communities

- **Local communities:** As noted above, conflict between communities and mining companies over mining projects is increasing, given the substantial negative impacts mining operations can have on local environments, public health, economies and livelihoods, and cultural resources. The IWG report notes that mining projects can, however, offer positive benefits to nearby communities if best practices are adhered to. Communities "can benefit from mining operations through job creation, economic development, new or upgraded infrastructure, educational scholarships and opportunities, and direct investment by a mining company in the community."

  Community Benefit Agreements (CBAs) and similarly named community and workforce agreements — including but not limited to Impact Benefit Agreements (IBAs), Host Community Agreements (HCAs), Good Neighbor Agreements (GNAs), siting agreements, Community Workforce Agreements (CWAs), and Project Labor Agreements (PLAs) — can be utilized as mechanisms to increase community acceptance of mining projects. Legally binding agreements, such as CBAs, can help ensure that benefits reflect actual needs of communities by including input from the affected community and are both well-planned and last beyond the conclusion of mining operations. These agreements can include local and targeted hiring commitments, the purchase of services and supplies from local vendors, investments in infrastructure, resources to allow the community to hire independent consultants to engage in monitoring and regulatory processes, and payments into a transition fund that could only be accessed upon a mine shutdown, among other benefits.

  Many grants and loans provided by the Department of Energy under BIL and IRA require applicants to submit a Community Benefit Plan, which is evaluated at 20% of the overall application; community agreements such as those mentioned above are strongly encouraged by these programs, which may provide funding to mining and materials processing initiatives. The DOE also sponsors programs that incentivize the transition of defunct mines into clean energy sites, including the Biden

[171] https://www.energy.gov/fecm/project-selections-foa-2854-front-end-engineering-design-studies-production-critical-minerals; https://www.usgs.gov/news/national-news-release/usgs-provides-2-million-states-identify-critical-mineral-potential-mine

[172] https://www.psu.edu/news/research/story/mission-critical-get-critical-minerals-and-rare-earth-metals-coal-waste/

Administration's $500 Million Program to Transform Mines Into New Clean Energy Hubs and the Qualifying Advanced Energy Project Credit (48C) Program.[173] Finally, the DOE's Critical Materials Program "coordinates research, development, demonstration, and deployment projects funded through multiple offices aimed at achieving DOE's vision to build secure, domestic critical mineral and material supply chains to support the clean energy transition while creating a just and sustainable future."[174]

- **Tribal communities:** Historical interactions between American Indian tribes and the mining industry can be characterized as complex and generally negative. Tribal concerns principally center around mining impacts to both natural and cultural resources as well as lack of consultation and coordination. Efforts to secure the materials to meet transportation decarbonization goals risk exacerbating and perpetuating these concerns: an analysis by MSCI found that the majority of lithium, nickel, and cobalt reserves in the U.S. are located within 35 miles of Native American Reservations (graphite and manganese were not analyzed).[175]

  Any mining activity that falls within the federal nexus triggers a variety of legal requirements to consult with Tribes and perform environmental review, including but not limited to the National Environmental Policy Act (NEPA) and the National Historic Preservation Act (NHPA). There are currently 574 federally recognized tribes in the United States and consultations with those tribes must be tailored to each tribe's unique history, make-up, and tribal organization. However, there are limitations to these consultation opportunities, as Tribal engagement may occur after significant resources have already invested in a project, or capacity issues such as limited staffing and funding to provide technical input on proposed projects.

  A renewed focus on mining should serve as an opportunity to improve Tribal consultation, in line with the Permitting Action Plan and the recommendations in the IWG report. "Early engagement with and consideration of impacts on Indigenous Peoples is widely accepted to be an industry best practice, is encouraged by a wide range of international organizations,…industry organizations,…foreign governments (such as Australia and Canada), and voluntary standards setting organizations."[176] Consultation should occur early, often, and in a meaningful way. Best practices for Tribal engagement are detailed further in the IWG report.

These approaches, when implemented strategically and collaboratively, could significantly strengthen U.S. supply chains, and ensure long-term resilience for critical minerals. The success of these potential options hinges on the robust collaboration of all key stakeholders, encompassing local communities, governmental bodies, industry, academic institutions, and research organizations.

173 https://www.energy.gov/articles/biden-administration-launches-500-million-program-transform-mines-new-clean-energy-hubs

174 https://www.energy.gov/cmm/critical-materials-project-search

175 https://www.msci.com/www/blog-posts/mining-energy-transition-metals/02531033947

176 https://www.doi.gov/media/document/mriwg-report-final-508-pdf

XII. CONCLUSION

Building upon existing literature, this study evaluates the proportion of upstream critical materials necessary to meet the U.S. EV and ES deployment targets. It assesses the potential contributions from both domestic upstream sources and non-U.S. sources. The study underscores the uncertainties and challenges in scaling the mineral supply from both mining and recycling. These challenges span a wide range, including environmental, geopolitical, and ethical dilemmas, maintaining economic feasibility, technical and technological hurdles, and potential financing issues.

The study also acknowledges certain limitations:

- **Data quality:** Some key project-level information, such as anticipated production capacities, closure dates, resources, or reserve levels, was missing or limited for some non-U.S. countries. This issue was more prevalent in some countries, such as China, Chile, and Argentina. To mitigate this problem, the study employed a combination of bottom-up and top-down approaches. Projections started with 2022 production for countries reported by USGS and added new capacity projections based on the bottom-up approach. Due to the lack of information on anticipated closure dates for several projects, it is possible that some projects have a shorter timeline than anticipated in this projection, leading to potential overestimations or underestimations. In general, for each project this study uses available information to make projections in line with the assumptions described in this study. As such, it is likely that actual project timelines and production capacities will vary.

- **Limited scope:** The study is limited in scope but could serve as foundation for further studies. Future areas of study could include evaluation of processing and refining capacities, especially as economic partner countries with abundant geological resources seek to add value midstream in the battery supply chain; examining potential shifts in trade flows based on project-level offtake agreements already secured by prospective projects; and evaluating MSP projects beyond the confines of MSP countries. Incorporating sensitivities to account for uncertainties could also be a valuable addition to future studies. Furthermore, developing cumulative supply curves for U.S. mines for assessed critical materials could provide a comprehensive assessment of the competitiveness of the U.S. in mining critical materials. Additionally, assessing the demand projections of other nations could provide insights into the proportion of potential global production that could be allocated to meet U.S. targets from EV and ES.

In conclusion, while this study identifies challenges, it illustrates that, for the five materials examined, the U.S. and its economic partners and allies in whole have significant geological resources of critical materials. These resources can be developed while also strengthening processing, refining, and recycling capabilities. The U.S. is engaged in a multifaceted approach to diversify the upstream critical minerals supply, which includes expanding domestic mining alongside non-U.S. sourcing strategies. Coupled with continued investments to develop critical minerals resources by the U.S. government, international allies and partners, and private industry, these efforts have the potential to secure the supply chain for U.S. EV battery materials.

It is essential that these efforts to build capacity and support infrastructure, secure financing, improve governance and transparency, and pursue innovative solutions are fully realized, both domestically and abroad. Furthermore, engaging communities to ensure that mining projects benefit local economies, support human rights, and minimize environmental impacts can secure buy-in for materials development and reduce risk. This comprehensive approach, which continues to expand as of the writing of this report, coupled with further research and demonstration in innovative materials and in the circular economy, will increase the diversity of global supplies needed to meet the demands of decarbonization with sustainable and secure critical mineral resources. As this report demonstrates, the global critical minerals supply chain of 2035 will likely look radically different from 2024, and there is great potential to realize this transformation towards a secure, diversified supply chain with the appropriate policy, diplomatic efforts, and investments in place.

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APPENDIX I: DEMAND PROJECTIONS METHODOLOGY

Appendix I describes the methodology and key assumptions used in estimating battery and material demand within the U.S.

a. Battery capacity demand estimation methodology

The process of estimating battery demand for EVs follows a bottom-up approach, employing TechScape's Material Demand Analysis Workflow (TechScape, 2023). Initially, projected EV sales are calculated for Light-Duty Vehicles (LDV), Medium-Duty Vehicles (MDV), and Heavy-Duty Vehicles (HDV). LDV sales figures are extracted from the BNEF EV outlook 2023 (BNEF, 2023), while MHDV sales projections are drawn from the NREL study on Decarbonizing Medium- & Heavy-Duty On-Road Vehicles (Ledna et al., 2022). These sales projections are then broken down by vehicle class and powertrain, using LDV class distribution overtime from the EPA OMEGA tool (U.S. EPA, 2023) and from the same NREL study for MHDVs.

Subsequently, considering the number of EVs in each class and their respective ranges, the total GWh of batteries is calculated. This estimation is based on the battery capacity per class obtained from Autonomie (Islam et al., 2023). Details on vehicle sales and class distribution are summarized in Table 9, Table 10, and Table 11.

Table 9. Vehicle sales projections.

Model Year	LDV	MHDV
2023	12,210,381	729,100
2024	12,993,196	741,400
2025	13,624,985	761,400
2026	14,101,064	782,900
2027	14,399,742	784,900
2028	14,660,458	796,800
2029	14,846,584	813,100
2030	14,995,001	818,100
2031	15,137,827	850,000
2032	15,278,130	862,500
2033	15,415,367	861,700
2034	15,502,272	884,900
2035	15,540,985	906,100

Source. LDV (BNEF, 2023), MHDV (Ledna C. et al., 2022).

Table 10. Share of light-duty vehicle classes.

Model Year	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Compact	8.1%	8.0%	8.0%	8.0%	7.9%	8.0%	8.1%	8.3%	8.2%	8.3%	8.3%	8.3%	8.3%
Midsize	19.1%	19.0%	18.8%	18.8%	18.8%	18.7%	18.9%	18.9%	19.3%	19.2%	19.4%	19.3%	19.4%
Small SUV	28.7%	28.8%	28.9%	28.9%	29.0%	29.2%	29.1%	29.3%	29.1%	29.3%	29.2%	29.3%	29.3%
Midsize SUV	29.5%	29.6%	29.6%	29.6%	29.6%	29.4%	29.3%	29.0%	28.9%	28.8%	28.8%	28.7%	28.7%
Pickup	14.6%	14.6%	14.7%	14.7%	14.7%	14.7%	14.6%	14.5%	14.5%	14.4%	14.3%	14.4%	14.3%

Source. U.S. EPA, 2023.

Table 11. Share of electric powertrains among MHDV classes

Low Scenario

Vehicle Class	Vehicle Purpose	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
3	Van	0.2%	0.3%	0.3%	0.4%	0.9%	2.0%	2.9%	4.0%	5.4%	7.3%	9.6%	12.3%	15.3%
4	StepVan	0.1%	0.1%	0.2%	0.2%	0.3%	0.6%	0.9%	1.2%	1.5%	1.9%	2.3%	2.8%	3.5%
6	Box	0.1%	0.2%	0.2%	0.3%	0.5%	0.9%	1.3%	1.8%	2.2%	2.7%	3.3%	4.1%	5.0%
7	Tractor	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
8	Longhaul	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.4%	0.5%	1.1%
8	Regional	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.2%	0.4%

Source. NREL (Ledna C. et al., 2022).

High Scenario

Vehicle Class	Vehicle Purpose	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
3	Van	0.2%	0.4%	1.0%	2.7%	6.3%	11.7%	15.9%	20.1%	23.8%	27.2%	29.7%	31.0%	31.3%
4	StepVan	0.1%	0.2%	0.4%	0.8%	1.7%	2.5%	3.3%	4.1%	5.1%	6.1%	7.0%	7.9%	8.5%
6	Box	0.2%	0.3%	0.6%	1.1%	2.4%	3.6%	4.8%	5.9%	7.4%	8.8%	10.1%	11.4%	12.3%
7	Tractor	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.3%	0.5%	0.7%	0.9%
8	Longhaul	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.6%	1.4%	2.6%	5.1%	8.8%	12.4%	15.0%
8	Regional	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.5%	1.0%	2.0%	3.4%	4.9%	5.9%

Source. NREL (Ledna C. et al., 2022)

b. Battery material estimation methodology

Estimates of material demand are derived from the battery GWh demand depicted in Figure 15 and the material content per kWh of various battery technologies projected for the market. The material content per battery technology is sourced from the Battery Performance and Cost (BatPaC) model (Argonne National Lab, 2023). Simultaneously, the battery market share across technology types is taken into account using data from BNEF EV Outlook 2023 (BNEF, 2023), adjusted to align with the battery technology received from the BatPaC developers at Argonne's Chemical Sciences and Engineering Division, as illustrated in Figure 48 and Figure 49. For ES batteries, it is assumed that the batteries are of the LFP type, given their high-power density, safety, very long lifespan, and low cost (Mongrid, 2019). Additional details on the material content from BatPaC for the various battery technologies considered can be reviewed in Table 12.

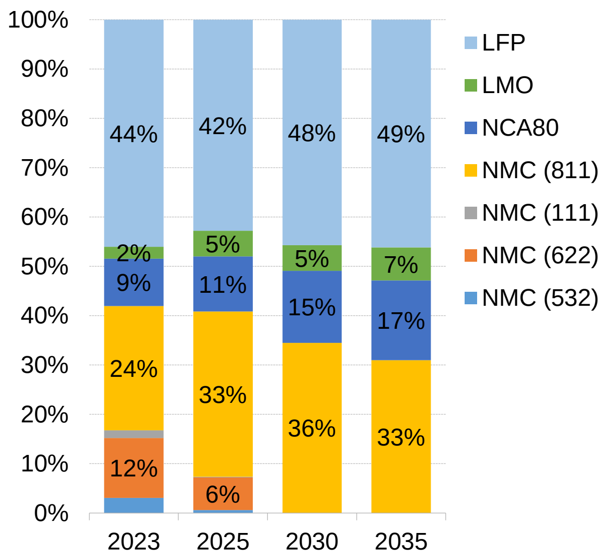

Figure 48. Evolution of cathode chemistry across all passenger EV segments.

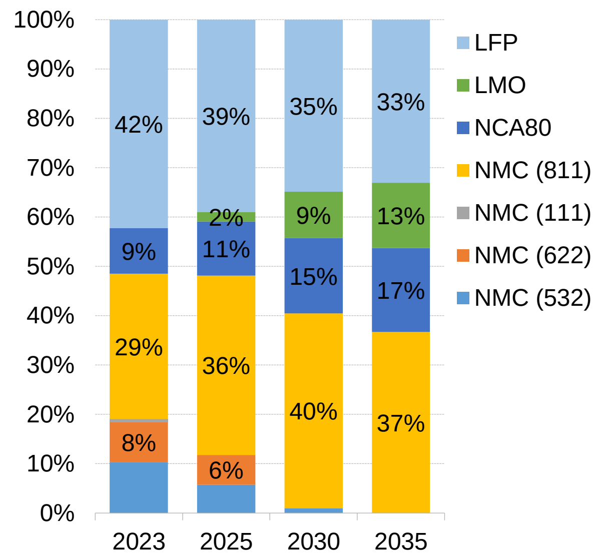

Figure 49. Evolution of cathode chemistry across all commercial EV segments.

Table 12. Material content from BatPaC for the various battery technologies

	NMC333-G (Energy)	NMC532-G (Energy)	NMC622-G (Energy)	NMC811-G (Energy)	NCA-G (Energy)	LFP-G (Energy)	LMO-G (Energy)
Cathode	NMC333	NMC532	NMC622	NMC811	NCA	LFP	LMO
Lithium, kg/kWh	0.13	0.12	0.12	0.10	0.11	0.10	0.11
Nickel, kg/kWh	0.37	0.50	0.59	0.70	0.75	-	-
Cobalt, kg/kWh	0.37	0.20	0.20	0.09	0.14	-	-
Manganese, kg/kWh	0.34	0.28	0.18	0.08	-	-	1.45
Anode	G	G	G	G	G	G	G
Graphite, kg/kWh	0.98	0.98	0.98	0.98	0.99	1.09	0.91

Source. Argonne National Laboratory (Knehr K. et al., 2023; BatPaC Model Software, 2023), accessed on May 5, 2023.

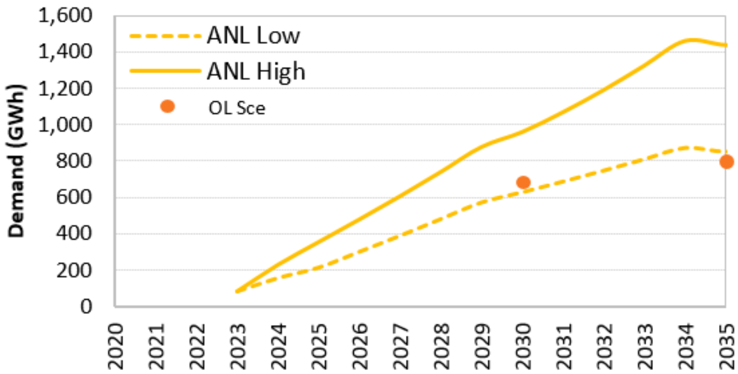

Figure 50. Comparison of Battery GWh between OnLocation and ANL Scenarios for Total LDV and MHDV EV Sales Projections.

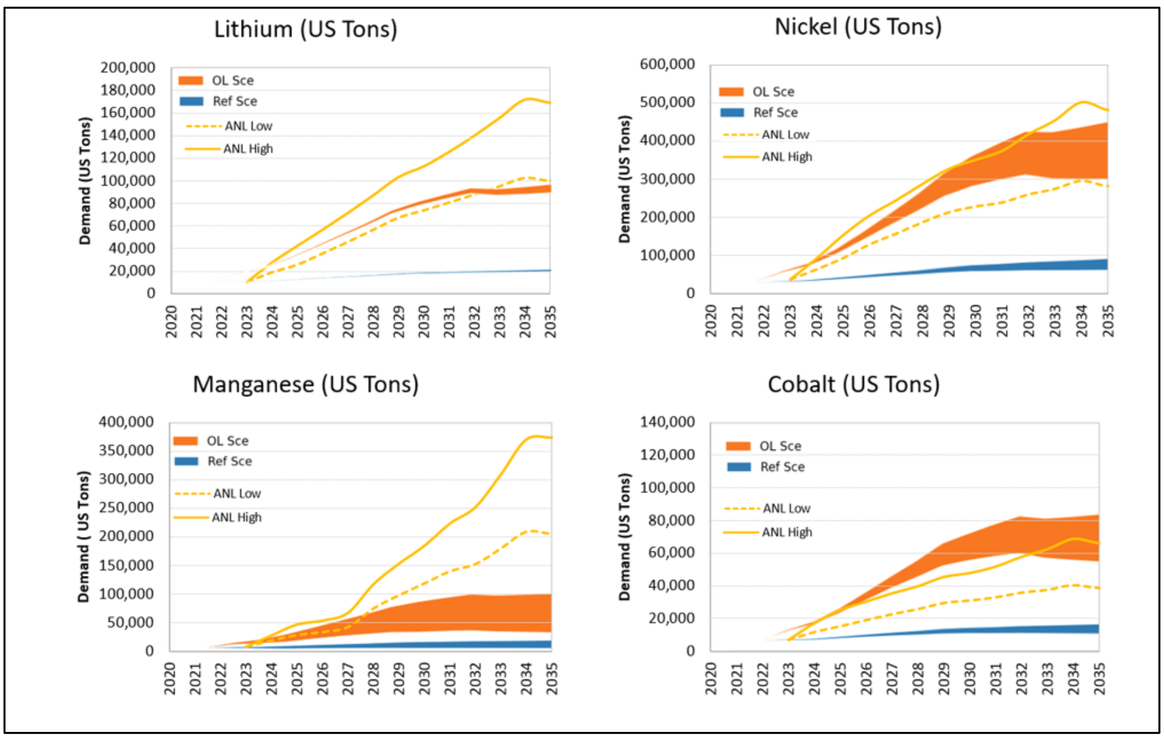

Figure 51. Comparison of material demand between OnLocation and ANL Scenarios for Total LDV and MHDV EV Sales Projections.

Note: ANL Scenarios assume the entire battery demand required will be manufactured from domestically sourced materials
Source. OnLocation, Inc. and KeyLogic Corp (De la Chesnaye F et al., 2023).

APPENDIX II: SUPPLY PROJECTION METHODOLOGY

Appendix II details the methodology behind the supply projections. Supply projections for lithium, nickel, cobalt, graphite, and manganese combined a top-down approach using country-level current production data from the USGS with a bottom-up approach using project-level data from S&P Global, supplemented by authors' research especially for domestic projects. 2023 production levels were estimated from USGS 2022 production data, assuming no change from 2022 to 2023. For countries not listed in USGS reports, but that contained project level operating capacities in the S&P Global data, 2023 aggregate production was estimated based on production capacities from the S&P Global data, with an assumed 90% capacity utilization.

Production after 2023 is assumed to increase as new capacity is added from projects in the S&P Global data, also assuming 90% capacity utilization. Assumptions in Table 13 are used to estimate anticipated start time for these projects. Authors used their expertise to map these assumptions to the development stage recorded in the S&P Global data and those reported elsewhere for domestic projects. Projects designated as inactive are not included in the projections. Projects with no production capacity in the S&P Global data are only included if they have completed or progressed further than a feasibility study, in which case production capacity is estimated as 2% of their reserves. Projected start times for some domestic projects are adjusted based on reviews of company reports and press releases. Notably, assumptions used in Table 13 are averages; in practice, the actual figures could vary depending on the country and complexity of the individual project. For instance, historical studies indicate that securing mining permits in the U.S. typically takes between 7 to 10 years. In contrast, the process in countries like Australia and Canada takes approximately two years.[177] There have been instances where U.S. mining projects have taken over 30 years to obtain a permit, with notable examples being the Rosemont Copper Mining and Resolute Copper Mining Projects in Arizona, and the Pebble Mining Project in Alaska. Conversations with mining experts reveal that permitting preparedness, such as paperwork, usually commences during the pre-feasibility mining development stage. However, with the incorporation of critical mineral projects into the FAST-41 program and proposed revisions in scope in 2023, it is anticipated that the permitting length in the U.S. will be reduced.[178]

177 https://mineralsmakelife.org/wp-content/uploads/2017/03/PermittingProcessFactSheet_FINAL_8.17.12.pdf

178 https://www.federalregister.gov/documents/2023/09/22/2023-20270/revising-scope-of-the-mining-sector-of-projects-that-are-eligible-for-coverage-under-title-41-of-the

Table 13. Anticipated years to production with no permitting delays

Mining project stage	Li, Mn, and Graphite	Ni and Co
Operating	0	0
Operating Partially	0	0
Close to Production	1	1
Under Construction	2	4
Planned Construction	3	5
Feasibility	5	8
Expansion	5	8
Prefeasibility	7	10
Preliminary studies	9	11
Exploration	Not included	Not included
Early Stage	Not included	Not included

Sources: Authors' assumptions estimated based on Albermarle Report, SNL Metals & Mining, 2015, S&P Global Market Intelligence, 2023, and expert consultation.

For nickel, an additional calculation was made regarding the portion of mining that was Class I nickel. The share of each country's production that was assumed to be Class I nickel is shown in Table 14. These shares were assigned based on analysis of USGS data on the mineral type used in each country, or for known deposits within the country[179,180], in some cases supplemented by additional reports. When both types of deposit were found, and absent additional information, 50% was assumed. Countries with sulfide deposits were assumed to supply Class I nickel, while countries with laterite deposits were largely assumed to supply Class II nickel, with exceptions for Indonesia and the Philippines, which are known to have operating HPAL plants producing Class I nickel.[181][182]

A limitation of this study is that we did not have information on anticipated closure date for projects outside of the U.S. If projects have a shorter operating timeline than anticipated in this projection, demand projections could be slightly higher than if we had a closure date for each project.

179 https://pubs.usgs.gov/myb/vol1/2018/myb1-2018-nickel.pdf

180 https://mrdata.usgs.gov/

181 https://www.woodmac.com/news/opinion/rise-of-indonesian-hpal/

182 https://www.smm.co.jp/en/sustainability/activity_highlights/article_12/

Table 14. Assumed Class I nickel shares by country

Country	Class I share of nickel produced
Australia	85%
Botswana	100%
Brazil	0%
Canada	100%
China	50%
Colombia	0%
Côte d'Ivoire	0%
Cuba	0%
Finland	100%
Greece	0%
Guatemala	0%
Indonesia	50%
Madagascar	50%
Myanmar	50%
New Caledonia	0%
Papua New Guinea	50%
Philippines	20%
Russia	97%
Solomon Islands	0%
South Africa	100%
Sweden	50%
Tanzania	50%
Türkiye	0%
USA	100%
Venezuela	0%
Vietnam	100%
Zambia	100%
Zimbabwe	100%

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