EERE R&D Battery Critical Materials Supply Chain Workshop Series

U.S. Department of Energy

Office of Energy Efficiency and Renewable Energy

Introduction

The purpose of this document is to provide background for the upcoming *EERE R&D Battery Critical Materials Supply Chain Workshop Series*, hosted by the Department of Energy (DOE)'s Office of Energy Efficiency and Renewable Energy (EERE). The goal of the workshop series is to determine opportunities, gaps, and bottlenecks in the battery cathode materials supply and the value chain. This workshop series will be driven by the goal to create a diverse, domestic battery supply chain in the next 5 years. EERE is specifically seeking input on the current state of the battery cathode materials supply chains and gaps and opportunities for near-term and long-term R&D.

In this document, we deliver a brief overview on critical materials and related supply chain challenges for industrially relevant battery-related applications. We also discuss strategic actions that have been undertaken by the U.S government to mitigate critical minerals supply chain risk. Further detail is provided on the role the DOE in advancing research and developent (R&D) of critical materials, while also highlighting significant activity within relevant Technology Offices in the EERE. Next, the goals of this workshop are discussed in more detail. Lastly, we include an analysis of the responses EERE received to the request for information released in June 2020. The analysis reviews the state of the industry with emphasis on battery cathode materials (such as lithium, nickel, cobalt and manganese cobalt). Additionally, we identify key trends, gaps and opportunities for development that will enable the creation of a diverse, domestic battery supply chain. This will serve as a starting point for discussion in the workshop series as we develop a complete R&D roadmap as part of implementation of *A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals*.

Background

Critical materials have major applications within many industries that are important to the U.S. economy and national security. They are essential for enabling the advancement of battery-related technology for a variety of applications. Battery critical materials such as lithium, cobalt, manganese, nickel, and graphite, contribute significantly towards the development of superior performing batteries that, in turn, will be important in the development of a viable battery supply chain. Lithium-ion batteries have become the primary option for portable electronics (such as smart phones, tablets, and laptops), power tools, and electric vehicles (EV) (U.S. Department of Energy, 2019). Demand for these materials is expected to increase; U.S. light-duty battery EV sales are projected reach 1.3 million by 2025 and global EV sales are expected to reach 30 million by 2030 (U.S. Energy Information Administration, 2019). Therefore, domestic lithium-ion battery development and production are needed to enable U.S. manufacturing competitiveness for energy technologies.

Of the 35 mineral commodities identified as critical in the list[1] published in the Federal Register by the Secretary of the Interior, the U.S. is 100% net import reliant for 14 (U.S. Geological Survey, 2020a) and is more than 50% import-reliant for 17 of the remaining 21 mineral commodities (U.S. Geological Survey, 2018). These critical minerals play a significant role in developing sustainable and high impact energy technologies. Despite the promise for these natural resources, adequate research and development is still required to transform these raw critical minerals into refined products for manufacturing. This development is imperative for establishing resilient supply chains.

Strategic Response

To reduce U.S. susceptibility to disruptions in the supply of critical minerals, the President issued Executive Order (EO) 13817, *A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals* (The White House, 2017). The EO directs the Secretary of Commerce, in coordination with heads of selected executive branch agencies and offices, to submit a report to the President that includes:

I. a strategy to reduce the Nation's reliance on critical minerals;
II. an assessment of progress toward developing critical minerals recycling and reprocessing technologies, and technological alternatives to critical minerals;
III. options for accessing and developing critical minerals through investment and trade with our allies and partners;
IV. a plan to improve the topographic, geologic, and geophysical mapping of the United States and make the resulting data and metadata electronically accessible, to the extent permitted by law and subject to appropriate limitations for purposes of privacy and security, to support private sector mineral exploration of critical minerals; and
V. recommendations to streamline permitting and review processes related to developing leases; enhancing access to critical mineral resources; and increasing discovery, production, and domestic refining of critical minerals.

The Department of Commerce (DOC) subsequently published the report to the President on June 4, 2019 (U.S. Department of Commerce, 2018).

Subsequently, in September 2020, the President issued EO 13953 on *Addressing the Threat to the Domestic Supply Chain from Reliance on Critical Minerals from Foreign Adversaries*. This directed agencies to examine potential specialists and prepare agency-specific plans to improve the mining, processing, and manufacturing of critical minerals. The response to this EO is underway; nevertheless, the U.S. Department of Energy (DOE) and supporting agencies have continued to engage in activities, such as stakeholder engagement, related to achieving the goals in the Executive Orders.

The Department of Energy's Role

The U.S. Department of Energy (DOE) assesses material criticality based on importance to a range of energy technologies and the potential for supply risk. To mitigate the risk for potential supply chain disruption, DOE coordinates research and development (R&D) around three pillars:

1. Diversifying supply of critical materials – including domestic production and processing;

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[1] Aluminum (bauxite), antimony, arsenic, barite, beryllium, bismuth, cesium, chromium, cobalt, fluorspar, gallium, germanium, graphite (natural), hafnium, helium, indium, lithium, magnesium, manganese, niobium, platinum group metals, potash, the rare earth elements group, rhenium, rubidium, scandium, strontium, tantalum, tellurium, tin, titanium, tungsten, uranium, vanadium, and zirconium

2. Developing substitutes; and
3. Driving recycling, reuse, and more efficient use.

The National Science & Technology Council (NSTC) Critical Minerals Subcommittee (CMS) is the interagency body that will coordinate implementation of the Federal Strategy. An organizing principle of this strategy is to address the full supply chain of critical minerals, which spans from securement of raw materials to end-uses in both civilian and defense applications. The strategy is organized around six Calls to Action, supported by 24 goals with corresponding specific agency level recommendations that will be pursued over the next five years. DOE is the lead for Call to Action 1 of the Federal Strategy: "Advance Transformational Research, Development and Deployment across Critical Mineral Supply Chains." In coordination with broad Federal agency input,[2] DOE will lead the development of a roadmap that identifies key R&D needs and coordinates on-going activities for source diversification, more efficient use, recycling, and substitution for critical minerals; as well as cross-cutting mining science, data science techniques, materials science, manufacturing science and engineering, computational modeling, and environmental health and safety R&D.

In June, 2020, DOE's Office of Energy Efficiency and Renewable Energy (EERE) issued a request for information (RFI) in support of Battery Critical Materials Supply Chain Research & Development (R&D). The purpose of the RFI was to solicit feedback from industry, academia, research laboratories, government agencies, and other stakeholders on issues related to challenges and opportunities in the upstream and midstream critical materials battery supply chains. EERE is specifically interested in information on raw minerals production, along with, the refining and processing of cathode materials including cobalt, lithium, manganese, and nickel.[3] The RFI was issued by the Advanced Manufacturing Office (AMO), in collaboration with the Geothermal Technologies Office (GTO) and Vehicles Technologies Office (VTO).

The interest in these critical materials is due to their significance for direct utilization in the fabrication of cathodes for lithium-ion batteries. There is a lack of supply diversity due in part to the limited domestic production facilities in the upstream supply chain. Although the U.S. has abundant sources of raw materials for lithium production, and potential for some domestic production of cobalt and nickel), there is limited domestic production of raw materials (< 1% of global mine production) (U.S. Geological Survey, 2020a).

Collaborating Offices

The mission of the Advanced Manufacturing Office (AMO) is to catalyze research, development and adoption of energy-related advanced manufacturing technologies and practices to increase energy productivity and drive U.S. economic competitiveness. AMO's strategic goals to achieve this mission include:

1. Improve the productivity, competitiveness, energy efficiency and security of U.S manufacturing;
2. Reduce lifecycle energy and resource impacts of manufacturing goods;

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[2] Other key coordinating agencies for Action 1 encompass the Department of Commerce (DOC) including the National Institute of Standards and Technology (NIST) and National Oceanic and Atmospheric Administration (NOAA); the Department of Defense (DOD), the Department of the Interior (DOI) including the United States Geological Survey (USGS), and the Environmental Protection Agency (EPA).

[3] Nickel is not a critical mineral commodity on the list published by the Secretary of Interior. However, it is also essential for cathode fabrication, and industrial stakeholders have expressed concern about the ability of the market to meet demand in the future

3. Leverage diverse domestic energy resources and materials in U.S. manufacturing, while strengthening environmental stewardship;
4. Transition DOE supported innovative technologies and practices into U.S. manufacturing capabilities; and
5. Strengthen and advance the U.S. manufacturing workforce.

In support of these goals connected to critical materials for lithium-ion batteries, AMO funds lithium-ion battery recycling and reuse R&D as part of the Critical Materials Institute (CMI), a DOE Energy Innovation Hub that is managed by Ames Laboratory. CMI's mission is to accelerate the development of technological options that assure supply chains of materials essential to clean energy technologies—enabling innovation in U.S. manufacturing and enhancing energy security. CMI's battery recycling efforts focus on physical, chemical, and biological approaches to recover precursor and elemental critical materials from end-of-life products.

AMO's activities also include the DOE Energy Storage Grand Challenge, which was announced in January 2020[4]. The vision for the Energy Storage Grand Challenge was to create and sustain global leadership in energy storage utilization and exports, with a secure domestic manufacturing supply chain that does not depend on foreign sources of critical materials. Using an organized group of R&D funding opportunities, prizes, partnerships, and other programs, the Energy Storage Grand Challenge includes following goal for the U.S. to reach by 2030:

> *Manufacturing and Supply Chain: Design new technologies to strengthen U.S. manufacturing and recyclability, and to reduce dependence on foreign sources of critical materials*

The Geothermal Technologies Office (GTO) researches, develops, and validates innovative and cost-competitive technologies and tools to locate, access, and develop geothermal resources in the United States. Beyond the traditional value that geothermal resources can provide for electricity or thermal applications, tapping into geothermal brines for valuable byproducts including critical materials presents a promising opportunity. Since 2014, GTO has funded two competitively awarded R&D solicitations focusing on mineral recovery from geothermal brines through novel extraction technologies, as well as better resource characterization for critical materials and rare earth elements in U.S. geothermal resources. However, commercial demonstration of mineral recovery from geothermal brines has not advanced beyond pilot scale and details of process and performance are known only to Intellectual Property (IP) owners and operators (including partly DOE-funded pilot demonstrations). In addition to supporting novel technology development, GTO recognizes the important co-location potential of hidden geothermal systems and critical materials deposits, and how acquiring data that supports the identification of these upstream resources is of significant strategic importance. The office is exploring opportunities to enhance the collection of data that leads to improved understanding of the distribution of lithium and other critical materials and hidden geothermal resources by enabling utilization of advanced machine learning techniques (U.S. Department of Energy, 2020).

The Vehicle Technologies Office (VTO) has a comprehensive portfolio of early-stage research to enable industry to accelerate the development and widespread use of a variety of promising sustainable

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[4] The Energy Storage Grand Challenge is a cross-cutting effort managed by DOE's Research and Technology Investment Committee (RTIC). DOE established the RTIC in 2019 to convene the key elements of DOE that support R&D activities, coordinate their strategic research priorities, identify potential cross-cutting opportunities in both basic and applied science and technology, and accelerate commercialization. The Energy Storage Subcommittee of the RTIC is co-chaired by the Office of EERE and Office of Electricity and includes the Office of Science, Office of Fossil Energy, Office of Nuclear Energy, Office of Technology Transitions, Advanced Research Projects Agency Energy (ARPA-E), Office of Strategic Planning and Policy Office of Policy, the Loan Programs Office, and the Office of the Chief Financial Officer.

transportation technologies. The research pathways focus on fuel diversification, vehicle efficiency, energy storage, and mobility energy productivity that can improve the overall energy efficiency and efficacy of the transportation or mobility system. VTO supports early-stage research to significantly reduce the cost of electric vehicle (EV) batteries while reducing battery charge time and increasing EV driving range. Over the past 10 years, VTO R&D has lowered the cost of EV battery packs by over 80% to $143/kWh in 2020 (Nelson et al., 2019). Current battery technology performance is far below its theoretically possible limits. Near-term opportunities exist to develop innovative technologies that have the potential to significantly reduce battery cost and achieve the operational performance needed for EVs to achieve cost competitiveness with gasoline vehicles. With these rapidly decreasing costs, there have been increased demand for battery materials for lithium-ion batteries. This has caused fluctuation and uncertainty in the battery materials supply chain. To mitigate potential lithium-ion battery supply risks, DOE has established following goal: By September 2022, reduce the cost of electric vehicle battery packs to less than $150/ kWh with technologies that significantly reduce or eliminate the dependency on critical materials (such as cobalt) and utilize recycled material feedstocks. To achieve this goal and address potential critical materials issues, VTO launched 3 key complimentary areas of R&D meant to reduce dependence on critical materials. VTO supports laboratory, university, and industry research to develop low-cobalt (or no cobalt) active cathode materials for next-generation lithium-ion batteries. VTO also established the ReCell Lithium Battery Recycling R&D Center in 2019 focused on recycling processes to recover lithium battery critical materials, and launched the Lithium-Ion Battery Recycling Prize to incentivize American entrepreneurs to find innovative solutions to solve challenges associated with collecting, storing, and transporting discarded lithium-ion batteries for eventual recycling to reduce battery disposition costs. VTO also participates with AMO in the recently launched Federal Consortium for Advanced Batteries (FCAB) which connects federal agencies that have interest in establishing a domestic supply of lithium-ion batteries and aims to accelerate development brings Federal agencies having a stake in establishing a domestic supply of lithium batteries together (U.S. Department of Energy et al., 2020).

Workshop Goals

Based on the directives and results from the RFI, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE)'s Advanced Manufacturing Office (AMO), Geothermal Technologies Office (GTO), and Vehicle Technologies Office (VTO) are hosting an R&D Battery Critical Materials Supply Chain Workshop Series to determine opportunities, gaps, and bottlenecks in the battery cathode materials supply and the value chain. This workshop will be driven by the goal to create a diverse, domestic battery supply chain in the next 5 years. EERE is specifically seeking input on the current state of the battery cathode materials supply chains and gaps and opportunities for near-term and long-term R&D.

Key question to address

Broadly, the workshop seeks to better understand the current and future trends of the upstream to midstream battery critical material supply chains for lithium, cobalt, and nickel; the gap and barriers for advancement of innovative technologies; and the capital and technical considerations for scaling from pilot to commercial production. We will focus on identifying impactful research and performance metrics for developing future research pathways for AMO/GTO/VTO specifically, as well as, integrated across broader EERE supply chain research. There will be an emphasis on identifying the need and gaps in capabilities related to lithium extraction from brines and hard rock. During this workshop, we hope to identify and establish additional metrics for consideration related to the broader supply chain for lithium extraction and to determine the criteria necessary for success in pilot-scale lithium extraction. There is also interest in understanding the different classes of direct lithium extraction (DLE) and recovery technologies available (Adsorption, Ion Exchange, Solvent Extraction), as well as, the R&D requirements to advance these technologies from the pilot-scale to commercial scale.

We will also address the fundamental question about the different sources of lithium (and other minerals) used, along with concerns on how lithium source will impact material purity, equipment design, secondary products, process economics and downstream applications. We want to develop an understanding of the different material sources, purities, and scales that are essential for material development. What purities for powders (including Li, Co, and Ni) are needed to be considered for battery grade applications and how are impurity studies performed? Our aim is also to identify problematic impurities and the impact transitioning to higher nickel cathodes and Li-metal anodes will have on purity. This workshop will also be directed at understanding the economic viability of US production from cobalt and nickel deposits, as well as, the most cost- and energy-efficiency pathways for conversion to cobalt and nickel sulfates. These materials (cobalt and nickel) will also be considered in relation to different facilities' ability to adapt to integrated processes that can accommodate multiple feedstocks (e.g., raw materials and secondary materials).

Related to cathode-manufacturing, there is a need to identify short-term and long-term materials for battery production. There needs to be an assessment and forecast to understand the potential position of battery materials within the next 5 years in relation to today's technology (oxide cathodes). Alternatively, will there be an opportunity for the development of new materials (such as Li for pre-lithiation and Li metal), and what are the most prospective materials? It is also imperative to identify the different components in batteries that may create problematic domestic supply chains (in the short term (1-3 years) and in the intermediate term (3-5 years)). We will also work on identifying the industrial/commercial and competitive landscape for battery manufacturing. We would like to know the scale where diversification of material sources become economic for lithium, nickel, and cobalt powder manufacturers. There is a need to identify the underlying economic drivers (e.g., length of contract), while outlining a description of any incumbent or other rapidly growing competing industries or uses for Li, Co, or Ni that have the potential to disrupt supply for battery manufacturing. Lastly, we will identify any bottlenecks that large battery material manufacturers experience as it pertains to mineral source, diversification and refining.

This workshop series will include a combination of planned talks from key representatives within DOE, as well as industrial stakeholders followed by extensive discussion sessions to review the key questions identified. We will employ interactive brainstorming tools to facilitate anonymous polls and short answer Q/A sessions and solicit responses from active participants and key stake holders. This input will inform the development of the R&D roadmap as part of implementation of *A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals*. This will also facilitate strategic planning and forecasting that will inform future directions in DOE's EERE programs (including R&D funding opportunities, prizes, awards, and partnerships). EERE plans to release a summary report following the workshop series.

Participants will be designated as "active participants" or "observers." Active participants will primarily be industry stakeholders to enable EERE to better understand the state of the industry, current and future challenges, and opportunities to address them. Observers will be asked to be in listen only mode during the workshop series, but will have the opportunity to provide feedback on the summary report before publication.

State of the Industry: Analyses from RFI

Cathode active materials like lithium, nickel, manganese, and cobalt are critical to the battery manufacturing industry in the U.S. The increasing demand for electric vehicles will further strain the supply security of these materials in the short-term. Given the current vulnerability of cobalt supply, and the projection of a global supply deficit by by 2025 (McKinsey & Company, 2018), the industry expects a shift towards “low cobalt” or “cobalt free” chemistries, though the latter will require significant investments to realize. This has resulted in a trend towards high nickel content cathodes (Figure 1. Projections of EV technology by battery chemistry (reproduced from McKinsey & Company 2018). Note: This figure is for illustration, and does not imply endorsement by the DOE.).

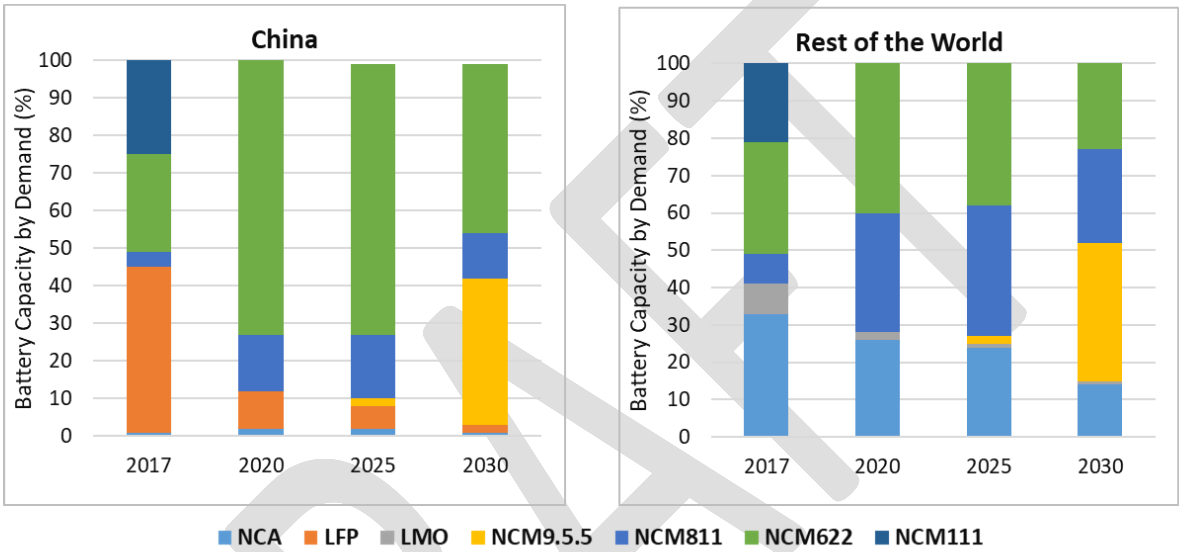
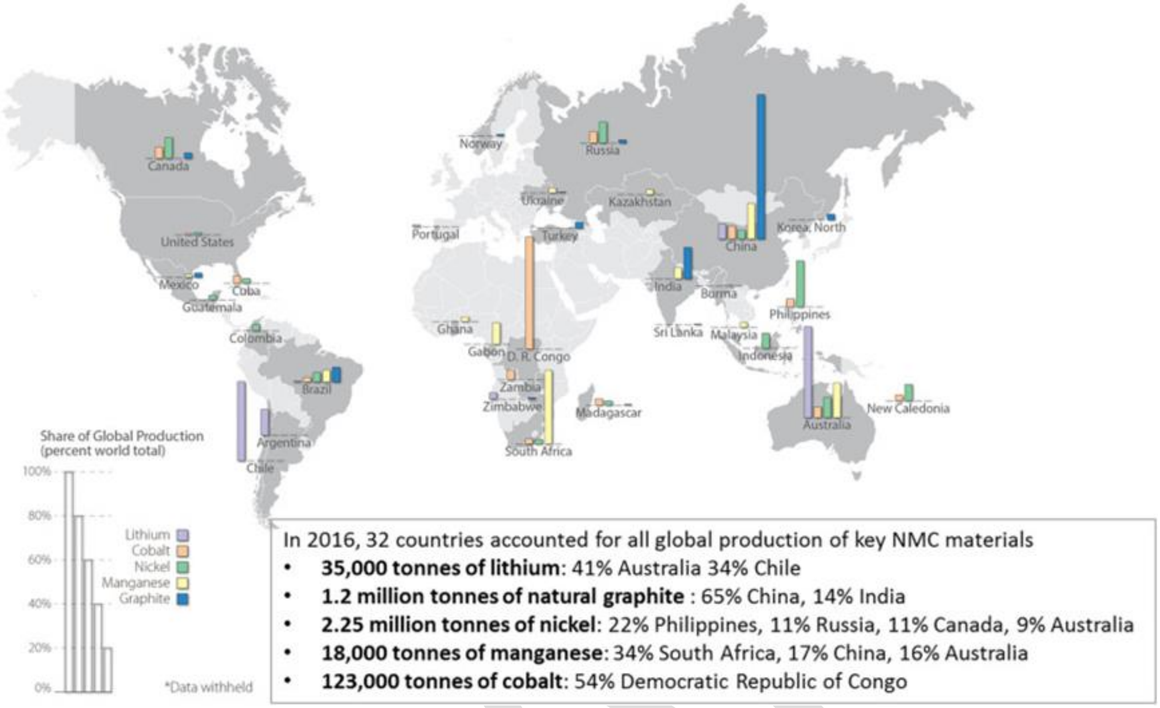


Figure 1. Projections of EV technology by battery chemistry (reproduced from McKinsey & Company 2018). Note: This figure is for illustration, and does not imply endorsement by the DOE.

In the face of these trends, supply security for these materials has become a key concern for the U.S, where there is little or no domestic production for these materials (see Figure 2. Lithium-ion battery-relevant mineral production by country (Mayyas et al., 2019).). The U.S. has significant deposits of lithium (in continental and geothermal brines and hard rock deposits), as well as other deposits for nickel and cobalt. Exploiting these domestic reserves can potentially improve resource security. However, this would require novel technologies and business models that reduce costs, reduce energy and chemicals intensity, improve environmental stewardship, simplify permitting and legal frameworks, leverage colocation, and ultimately de-risk investments.

Lithium

Lithium currently has very limited domestic supply, though the US has significant resource potential in continental and geothermal brines and hardrock deposits. The industry anticipates an increase in lithium demand to leverage the potential from increased energy density from high nickel content (see Figure 3), though this faces cycle life stability issues. However, with the arrival of Giga- and Tera-factories on the horizon, adequate supply may be challenging in the short-term. This is due in part because low market prices discourage the expansion needed to keep pace with global demand, and it takes several years to develop a new mine project and even longer to develop a productive salar brine. While the potential for lithium extraction from US brine reservoirs is huge, the industry trend towards higher energy density cathodes (e.g., NMC811[5]) means that the intermediate carbonate step from brine to lithium hydroxide adds cost and energy intensity penalties. This highlights a major R&D opportunity.



In 2016, 32 countries accounted for all global production of key NMC materials

- **35,000 tonnes of lithium**: 41% Australia 34% Chile
- **1.2 million tonnes of natural graphite** : 65% China, 14% India
- **2.25 million tonnes of nickel**: 22% Philippines, 11% Russia, 11% Canada, 9% Australia
- **18,000 tonnes of manganese**: 34% South Africa, 17% China, 16% Australia
- **123,000 tonnes of cobalt**: 54% Democratic Republic of Congo

Figure 2. Lithium-ion battery-relevant mineral production by country (Mayyas et al., 2019).

Opportunities & need areas

Traditional processes for extracting and processing lithium can be process intensive, and costly. Among other challenges, extraction of lithium from continental brine or hard rock resources requires several process steps and consumes large quantities of reagents. Brine evaporation requires very long lead-time (~2 years[6]) and heavy land use for solar evaporation, and has relatively low extraction efficiencies. R&D opportunities that can address these challenges include developing electrochemical processes for direct lithium extraction – which reduces reagent use and eliminates intermediate energy intensive steps -, developing functionalized solvents selective towards lithium, eliminating dependence on caustic chemicals (e.g., CO_2 in place of acid for stripping) and developing process-integrated removal of toxic impurities from tailings.

Cobalt

Like lithium, there is limited domestic production of cobalt in the US - <1% of global production (Burger et al., 2018) – with most production as byproducts from copper or nickel mining, and a significant proportion from secondary production. The Democratic Republic of Congo accounts for nearly 65% of global mine production, with most of the processing occurring in China. While current battery chemistry

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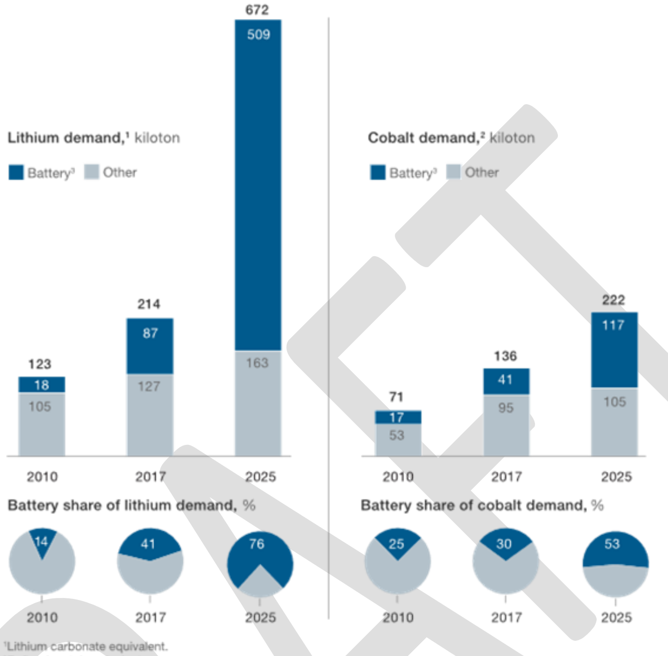
[5] NMC refers to Nickel-Manganese-Cobalt and 811 refers to the chemical composition of those elements in the lithium-ion battery cathode (LiNi0.8Mn0.1Co0.1O2)

[6] Estimates from responses to the RFI ranged from 1.5 to 2.5 years

is expected to stay course in the next five years (shown in Figure 3), the industry expects a shift towards "low cobalt" or "cobalt free" chemistries in the longer term, primarily for reasons of supply security, and in response to anticipated cobalt shortage by the middle of the next decade. Secure domestic supply could reduce the urgency for the shift, but there is almost no appreciable domestic supply of cobalt in the US, and known deposits are often too small and too low-grade to leverage economies of scale.



[1] Lithium carbonate equivalent.
[2] Refined metal equivalent.
[3] Includes automotive (hybrid-, plug-in hybrid-, and battery-electric vehicles), trucks and buses (light, medium, and heavy), two and three wheelers, machinery (forklifts and others), grid storage, and consumer electronics.
Note: Figures may not sum to listed totals, because of rounding.

Figure 3. The industry expects anticipates an increase in both lithium and cobalt demand in the short-term (McKinsey & Company, 2018). Note: This figure is for illustration, and does not imply endorsement by the DOE.

Opportunities & need areas

Cobalt mining faces the challenge of high specific cost (due to low-grade, small quantity deposits), high energy and process intensive steps. R&D to advance in-situ leaching can reduce mine development and reclamation costs. Development of eco-friendly and cobalt-selective solvent and extraction agents can improve specific yield and reduce environmental impacts. Novel process configurations that eliminate energy intensive steps (like smelting), electrify production process (with the option of integrating renewables), and reduce tailings dam can improve both economics and environmental impacts. Integration of artificial intelligence and data analytics can reduce geological resource survey and characterization costs

Nickel

As the industry shifts towards "low cobalt" (or "cobalt free") and nickel-rich cathode chemistries, the demand for high-grade nickel will increase in tandem. EV demand for nickel is projected to grow by an order of magnitude from 2018 to 2025 (Statista, 2019). However, manufacturers have to deal with the difficulty of meeting the high cathode active material purities required by these nickel-rich cathodes. Like lithium and cobalt, US domestic nickel production is low (<1% of global mining), with the largest reserve in Indonesia (U.S. Geological Survey, 2020b). Like cobalt, domestic (terrestrial) nickel deposits are limited, and often low-grade. The combination of high permitting costs and low economies of scale makes extraction economics challenging, often requiring the development of co-product business models to de-risk investment. The difference is that unlike cobalt, nickel demand is trending upwards

Opportunities & need areas

Nickel mining also faces the multifaceted challenge of high specific cost (low economies of scale), high energy and process intensity. The same opportunity for R&D technology and capability development as for cobalt apply here, with emphasis on novel processes that reduce reliance on acids for separation and precipitation, and synergistic extraction agents to improve selectivity and reduce process steps. A significant supply of nickel comes from recycled streams, which positions it to leverage advances in process intensification

Other battery-relevant critical materials

Other battery-relevant critical materials include manganese, which is set to increasingly replace cobalt in battery electrodes, and for which there is virtually no US mine production as of 2019; graphite, also with virtually no US production, and while not supply-constrained, is largely sourced from politically unstable regions of the world (Robinson Jr. et al., 2017); and rare earth minerals, with concentrates from Mountain Pass accounting for 12% of global production, but shipped to China for processing (Van Gosen et al., 2017).

Opportunities & need areas

The similar supply chain risks and opportunity for R&D technology and capability development apply.

Summary of RFI Responses

AMO received a total of 42 responses to the RFI. Summaries of RFI responses to questions in key areas of interest identified in the RFI are provided below. The content of these summaries is based solely on the collective information and comments provided by RFI respondents. DOE does not endorse or oppose any claims, assessments or views expressed by RFI respondents, and the summary is intended to act merely as a primer for facilitating fruitful discussions during the workshop.

Future battery chemistries and material supply

Stakeholders do not anticipate cathode chemistry to change considerably. However, a move towards nickel-rich cathode compositions and solid electrolytes is deemed likely due to factors such as concerns about cobalt sourcing, design needs for higher energy density and longer cycling stability, and battery safety. Anodes are expected to shift to a combination of graphite and Si-based or Li metal-based compositions. Battery systems based on ions beyond lithium, including sodium and potassium-based chemistries, are also of interest, but over a longer R&D timeline.

Large cathode producers seek 5 to 10 kilotonnes of materials to qualify new sources and Gigafactories ideally source from 4 to 5 difference sources of materials, which are not yet available domestically. Lack of adequate mineral resources for domestic mining and processing infrastructure for intermediates makes the supply of *all* active battery materials a concern. Nickel-rich chemistries would require greater supply of battery quality nickel, and this would lead to greater competition for nickel with metal alloy manufacturers. Similar concerns about material competition from the primary metals manufacturing industry exist for cobalt and manganese as well. Other competing applications for cobalt include catalysts. Li demand, on the other hand, is largely driven by the battery industry.

Purity requirements for nickel, lithium, and cobalt vary by end-use storage application, source of the metal (e.g., hydroxide vs. carbonate), and battery chemistry/composition. Whereas 98-99.5% purity is generally regarded as battery grade, use of these materials in EVs or specialized higher energy applications puts more stringent standards on the types and concentrations of impurities allowed. In general, higher nickel content cathodes have lower impurity tolerance of precursors, typically in the range of 50 to 200 ppm. Magnetic impurities pose the greatest challenge, with impurity tolerance as low as 1000 ppm. The location of impurities is also important. Impurities on surface of the electrode can hinder manufacturing and performance, while some impurities in the bulk are known to enhance structural stability and cycle life.

Economics and battery supply chain

Diversification of battery material sources is viewed as being driven by material prices and reliability of supply. To this end, it is critical to understand and explicitly model the decision-making process and the various stakeholders involved in financial and non-financial decisions around mine openings, expansions and closures, stockpiling, and supply disruption risk management. Longer contract length is important for de-risking price changes, and for mining operations, guaranteed access to ores and proximity to ore processing and transport infrastructure are needed in addition to long-term contracts. It must also be considered that developing and qualifying any new sources takes several years and investors who are willing to bear considerable financial risk. Further, a diversified material source base would require refining facilities to be designed to work with a range of impurity types and quantities.

Transportation does not constitute a large fraction of costs, particularly for high-value materials, and as such decisions about co-locating intermediates processing facility near raw material sources may not be driven by cost considerations alone. Co-location would, however, reduce risk of supply disruptions, inventory costs, and losses. Processing of intermediates into products is recommended to be housed under the same facility due to higher costs and losses associated with specialized transportation that may be needed (e.g., vacuum/inert atmosphere transportation of lithiated cathodes). For example, the high costs of sulfate transportation make colocation with cathode production desirable. Finally, co-location may offer a clear and viable way of reducing carbon emissions from the battery supply chain.

Assuming that a giga-factory would produce about 20 GWh of battery storage products, needing about 1.4 tonnes of active cathode materials per GWh, the total demand at this scale could be met by a single supplier. A single supplier would be beneficial for ensuring stringent material quality requirements. However, this advantage must be weighed against the supply risk mitigation value offered by multiple suppliers. Under a multiple supplier scenario, a giga-factory may have 2 to 3 suppliers for nickel, lithium, and cobalt, with each supplier potentially obtaining and processing its materials from 1 to 3 material sources.

Lithium powder processing including geothermal brines

Conventional lithium extraction process is energy and chemical-intensive because of the multiple high-temperature separation processes involved. Direct lithium extraction is seen as a promising way of reducing both the energy and chemical intensity by reducing the number of process steps through the use of highly selective adsorbents, precipitants, catalysts and/or electrolysis. Energy and chemical intensities are also tied to purity of lithium. Nickel-rich battery chemistries could lower energy and chemical intensity by enabling the use of lower-purity $LiOH/Li_2CO_3$ blends. Electrification of mining equipment and processes is seen as another process intensification and energy efficiency measure.

In processes involving conversion of Li_2CO_3 to LiOH, energy and chemical intensity could be reduced through better recycling of hydroxide reagents, novel separation methods such as CO_2-based striping of Li instead of acid-based stripping, concentration of brines via reverse osmosis, and co-location of refining processes with upstream raw material extraction processes to reduce transportation. Steam flashing of produced geothermal brines could also create opportunities for capturing the resulting CO_2 and subsequently sequestering the captured CO_2 in carbonate form. Electrochemical processes that convert LiCl to LiOH without needing intermediate conversion to Li_2CO_3 could reduce energy intensity. However, such processes would need tight control of calcium and manganese concentrations in the brine to prevent membrane fouling.

The life cycle environmental impact of lithium extraction and processing must also be considered. Use of toxic and caustic reagents, substantial water use, mine tailings, and large land footprint (hard-rock reserves can sometimes be adjacent to existing communities; brines take up considerable space for evaporation ponds) are just some of the key deleterious impacts of the process. In attributing process impacts in a multi-output process such as lithium extraction, careful attention must be paid to economically useful co-products as well. With appropriate application, direct lithium extraction is a technology that could possibly mitigate many of these environmental impacts.

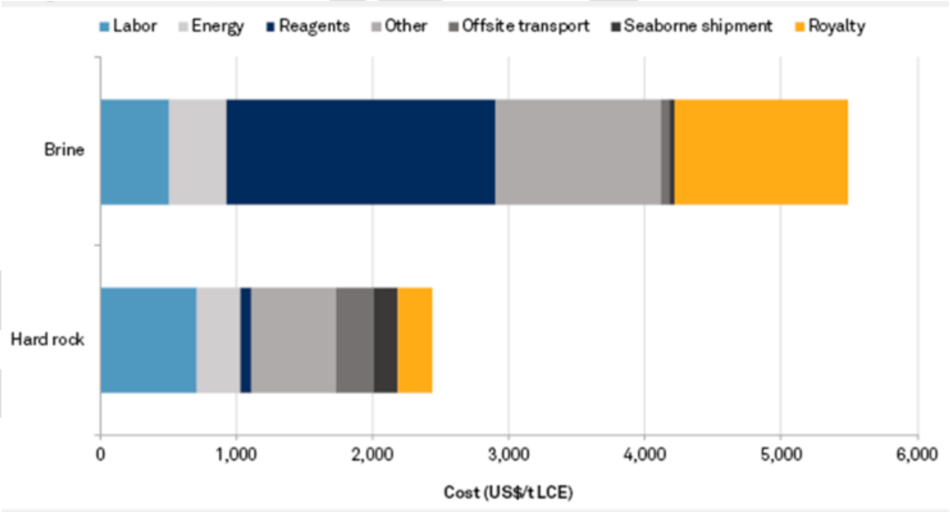


Figure 4. Comparing the cost of lithium extraction from hard rock vs brine. Royalty refers to reagent royalty costs. (S&P Global, 2019). Note: This figure is for illustration, and does not imply endorsement by the DOE.

Both hard-rock mining and continental brines as a source of lithium present unique opportunities and challenges in the U.S. context. Brines generally have very high reagent costs (see Figure 4) and need several years before useful lithium output could be produced. Hard-rock mining on the other hand generally has lower operating expenses, can yield useful output in about 18 months, and affords greater control over mine plans, raw material stockpiles, and feed conditions. While they have been successful elsewhere in the world, differences in permitting, governance, land use, and lack of technology commercialization expertise and experience have limited the success of these technologies so far in the U.S.

Adsorption or ion exchange-based approaches are identified as holding the greatest promise for extraction of lithium from geothermal brines, both from an economic and environmental standpoint. Ion exchange may face temperature limitations while adsorption and solvent extraction-based approaches need to address selectivity issues for lithium. There are also safety concerns surrounding the volatility of organic solvents when used in solvent extraction in a geothermal environment.

Lithium extraction from geothermal brines should consider a range of metrics in working towards implementing appropriate technology successfully. These include freshwater availability, brine temperature, distance between brine production and waste injection wells, impurity profiles (iron, manganese, zinc, silica, etc.), process yield, chemical additives consumption, ability to monetize byproducts, and transportation infrastructure.

Identifying lithium geothermal brine resources is relatively straightforward. However, high drilling costs, difficulty in obtaining permits, high pre-concentration times, and lack of a clear process technology option are key barriers. Economic incentives akin to those seen in oil and gas drilling could be explored to reduce drilling costs. Resource characterization could help by estimating attributes such as concentration, continuity, abundance and ease of access.

For a pilot scale lithium extraction plant to be successful, its capital cost in terms of $/tonne of Li_2CO_3 equivalent must not be prohibitive. Unfortunately, direct lithium extraction and electrochemical processes both currently face high capital costs. Process integration, optimization and green design should be employed to minimize the use of natural resources including land, water, and primary energy, as well as to reduce or eliminate the use of toxic reagents and waste products. The equipment and feedstock used in a pilot plant must also be representative of real commercial operations.

Cobalt and Nickel Processing

Known deposits of CoAs are low-grade and limited such that mining just for cobalt may not be economical with existing technology that requires economies of scale. Environmental and health impacts of arsenic and sulfides remain key issues to mining of cobalt from CoAs. In-situ leaching can reduce mine development and reclamation costs by removing need to excavate ore. However, such processes should not use toxic or expensive leaching agents. High-temperature roasting and high-pressure leaching is required to eliminate arsenic. Costs could also be reduced by using solvent systems that are selective towards cobalt (and other preferred elements that are co-extracted) and have desirable electrochemical properties that favor electrowinning.

For nickel, high-quality deposits are rare and processing techniques are complex and have high energy requirements. U.S. deposits tend to be sulfide bodies which are ideal for Class I nickel production, but further chemical/spatial exploration and characterization of deposits and faster permitting processes are needed. Subsea nickel resources in U.S. Pacific Territories could be explored, but this would need legal and regulatory support. There is also an opportunity to simplify the extraction process and reduce energy intensity by directly converting ore concentrate to nickel sulphate using electrochemical processes. It is noted that mine production timeline for high grade nickel mines is slower than low-grade copper-nickel mines since the former requires access to road, rail and power infrastructure and smelters.

Most nickel refining is vertically integrated or located in China. To develop and expand nickel refining in the U.S., we need to secure access to nickel intermediates or nickel concentrate from our strategic international allies, or responsibly explore domestic mines in regions such as Minnesota and Michigan. It should be noted that current nickel prices do not support investment in new mines and processing facilities with high capital costs, unless nickel prices reach closer to $20/kg. One approach to reduce refining costs and plant size is to explore deep eutectic solvents that could eliminate the solvent extraction stage.

Alternate routes to produce battery grade nickel must also be explored. It should be noted that not all Class I nickel is battery grade (e.g., difficult to leach full plate cathode) and some Class II nickel is suitable as battery grade (e.g., mixed hydroxide precipitate). Recycling should also be a key focus for domestic production of nickel, given that 68% of nickel in consumption is from recycled sources. Hydrometallurgical recycling process involving solvent extraction, electro-refining and electrowinning can be used to extract nickel from secondary sources including spent lithium-ion and NiMH batteries. Nickel extraction from recycled batteries could have lower energy and chemical intensity efficient than ore refining because recycled batteries have lower levels of impurities and higher concentration of nickel.

Energy and chemical intensity of nickel could also be reduced by co-locating smelters, which significantly reduces transportation energy use, emissions, and costs. Nickel could be transformed into cathode precursors at the source site. Redesigning the process to recycle water run-off for material processing, recovering and using waste heat and steam within smelting and refining processes, eliminating tailings dam, and improving geological survey methods by leveraging artificial intelligence and data analytics are some other approaches suggested to reduce energy and chemical intensity of nickel production. Using renewable sources of electricity to power a variety of pyro-, hydro- and vapor-metallurgy processes can reduce greenhouse gas emissions. Process optimization and green chemistry could be explored as ways to reduce consumption of chemical reagents and minimize the quantities and impacts of mine tailings.

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