U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Battery Critical Materials Supply Chain Challenges and Opportunities:

Results of the 2020 Request for Information (RFI) and Workshop

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Preface

The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Advanced Manufacturing Office (AMO) partners with industry, small business, universities, and other stakeholders to identify and invest in emerging technologies with the potential to create high-quality domestic manufacturing jobs and enhance the global competitiveness of the United States. 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. The Vehicle Technologies Office (VTO) supports research, development, and deployment of efficient and sustainable transportation technologies that will improve energy efficiency, fuel economy, and enable America to use less petroleum.

This document was prepared as a collaborative effort between DOE AMO, GTO, and VTO, Argonne National Laboratory, and Energetics.

Acronyms and Abbreviations

AI	Artificial Intelligence
Al	Aluminum
AMO	Advanced Manufacturing Office
Ar	Arsenic
ATVM	Advanced Technology Vehicles Manufacturing
BEV	Battery electric vehicle
C	Carbon
°C	(degrees) Celsius
Ca	Calcium
CFO	Office of the Chief Financial Officer
Cl	Chlorine
Cl^-	Chloride
CMI	Critical Materials Institute
CMS	Critical Minerals Subcommittee
Co	Cobalt
CO_2	Carbon dioxide
CO_3	Carbonate
Cr	Chromium
Cu	Copper
DLE	Direct Lithium Extraction
DOC	U.S. Department of Commerce
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DRC	Democratic Republic of the Congo
DSTP	Deep-sea tailings placement
EIA	U.S. Energy Information Administration
EERE	Office of Energy Efficiency and Renewable Energy

E.O.	Executive Order
EPA	U.S. Environmental Protection Agency
ESGC	Energy Storage Grand Challenge
EV	Electric vehicle
FCAB	Federal Consortium for Advanced Batteries
Fe	Iron
FECM	Office of Fossil Energy and Carbon Management
GTO	Geothermal Technologies Office
GWh	Gigawatt-hour
H	Hydrogen
H_2	Molecular Hydrogen
HEV	Hybrid electric vehicle
HPAL	High pressure acid leaching
IC	Ion chromatography
ICP-MS	Inductively coupled plasma mass spectroscopy
IEA	International Energy Agency
IP	Intellectual Property
K	Potassium
kg	Kilogram
kt	Kiloton
ktpa	Kilotonnes per annum
KTPY	Thousand tonnes per year
kWh	Kilowatt-hour
LDV	Light-duty vehicle
LFP	Lithium-iron-phosphate
Li	Lithium
Li_2CO_3	Lithium carbonate
LiOH	Lithium hydroxide
LPO	Loan Programs Office

Mg	Magnesium
Mn	Manganese
MWh	Megawatt-hour
Na	Sodium
Na2SO4·10H2O	Sodium sulfate decahydrate
NE	Office of Nuclear Energy
Ni	Nickel
NIST	National Institute of Standards and Technology
NMC	Lithium-Nickel-Manganese-Cobalt-Oxide ($LiNiMnCoO_2$)
NOAA	National Oceanic and Atmospheric Administration
NSTC	National Science and Technology Council
O	Oxygen
O_2	Molecular Oxygen
OE	Office of Electricity
OEM	Original equipment manufacturer
OES	Optical emission spectroscopy
OH	Hydroxide
OS	Office of Science
OSTP	Office of Science and Technology Policy
OTT	Office of Technology Transitions
PHEV	Plug-in hybrid electric vehicle
ppm	Parts per million
Q&A	Questions and Answers
R&D	Research and Development
RDD&D	Research, Development, Demonstration, and Deployment
RTIC	Research and Technology Investment Committee
RFI	Request for Information
S	Sulfur
SEI	Solid electrolyte interphase

Si	Silicon
SiO	Silicon Oxide
SiO_4^{2-}	Sulfate
TRL	Technology Readiness Level
µm	Micron (micrometer)
U.S.	United States
USGS	United States Geological Survey
UV	Ultraviolet
VTO	Vehicle Technologies Office
Zn	Zinc

Executive Summary

The purpose of this report is to outline and discuss the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE)'s findings related to EERE's Request for Information (RFI) on Battery Critical Materials Supply Chain Research & Development (R&D) and the EERE R&D Battery Critical Materials Supply Chain Workshop. The United States has committed to achieving 50% or more reduction of greenhouse gas pollution by 2030, with a long-term goal to completely decarbonize the U.S. economy by 2050, and to limit global warming to 1.5 degrees Celsius (The White House, 2021a). The clean energy technologies that will facilitate the realization of these goals require a substantial amount of critical minerals and materials, but these currently have limited production pathways and supply chains risks. To better understand the nature of the problem and develop solutions to facilitate improvements in this industry, EERE solicited feedback and input from subject matter experts and industrial stakeholders.

The RFI was issued on June 29, 2020, to solicit feedback from industry, academia, research laboratories, government agencies, and other stakeholders on the challenges and opportunities in the upstream and midstream critical battery materials supply chains (DOE, 2020a). There was specific interest in information on raw minerals production, along with the refining and processing of cathode materials such as cobalt, lithium, manganese, and nickel. Subsequently, the workshop was held in December 2020, and it featured three days of focused discussions on matters related to lithium, nickel, and cobalt supply security, as well as cathode manufacturing, with an overarching goal of creating a diverse, domestic battery supply chain in the next five years. There was a particular focus on the current state of the battery cathode materials supply chains and gaps in and opportunities for both near-term and long-term R&D. Both the RFI and the workshop were coordinated by EERE's Advanced Manufacturing Office (AMO), in collaboration with its Geothermal Technologies Office (GTO) and Vehicles Technologies Office (VTO).

The major themes identified in the report are resource characterization, technology, energy, and chemical intensity, scale-up, economics, and environment. Key takeaways discussed include the need for opportunities to validate technologies at the pilot scale; increased connectivity across the supply chain; and developing a strategy that prioritizes resource diversification. The report finds that a major challenge restraining the extraction and processing of lithium from brine and hard rock resource is the limited scale-up investment into deployment-ready technologies for separation and purification. Therefore, making R&D funding available can go a long way to de-risk new technologies, reduce the cost of capital, and improve overall project economics. Process intensification and energy integration can improve the energy and chemical intensity of lithium extraction, while repartitioning the lithium brine value chain can enable a degree of vertical integration from resource owners to technology providers.

The input from the RFI and workshop also indicated that nickel and cobalt supply security require a strategy that prioritizes resource diversification since projected secondary streams from end-of-life batteries could become a significant domestic source for both resources. Therefore, funding opportunities for both early-stage R&D and high technology readiness level (TRL) technology transitions for primary and recycled resource processing will strengthen U.S domestic manufacturing and reduce dependence on foreign sources of critical materials. Additionally, resource purity is of significant concern with nickel or cobalt making separation and purification technologically challenging. Thus, R&D directed at reducing processing costs – from pre-treatment to refining – can lead to economically competitive solutions.

The cathode manufacturing industry anticipates a shift towards nickel-rich cathodes followed by a transition towards cobalt-free chemistries, although long-term agreements for cobalt supply coupled with increasing lithium-ion battery demand will continue to make cobalt an important commodity. The industry also expects new anode materials to include hybrid graphite/silicon, as well as anodes based on metallic lithium, foils, and films. With newer lithium sources, clear definitions of the purity requirements for different stages of precursor material are needed, as well as which forms of impurities are more critical than others. Such definitions are an

important step in developing standards for domestic cathode manufacturing. Lack of clear definitions effectively represent barriers and risk. Funding for early-stage technology performance and increased connectivity across the supply chain can overcome these key barriers and de-risk future investment in technology scale-up, which can attract R&D investment.

Input from the workshop 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 EERE programs to include R&D funding opportunities, prizes, awards, and partnerships. EERE will continue to coordinate and collaborate with stakeholders in battery critical material supply chains to address the risks and capitalize on the opportunities identified in this and other reports.

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Introduction

Background

The United States has committed to achieving 50% or more reduction of greenhouse gas pollution by 2030, with a long-term goal to completely decarbonize the U.S. economy by 2050, and to limit global warming to 1.5 degrees Celsius (The White House, 2021). As part of these efforts, the United States is working to achieve 100% clean electricity by 2035. The clean energy technologies needed to achieve these goals, such as electric vehicles (EVs) and grid energy-storage needed to expand the use of renewable electricity generation, require a significant volume of critical materials (International Energy Agency (IEA), 2021).

As a result of these developments, the transition to clean energy technologies is projected to drive demand for many raw critical minerals, such as lithium (Li), cobalt (Co) and nickel (Ni), for lithium-ion batteries used in EVs.[1] These critical materials are used to fabricate cathodes for lithium-ion batteries. By 2030, annual sales for U.S. light-duty EVs[2] sales alone are projected to reach approximately 1.3 million (U.S. Energy Information Administration (EIA), 2021) while annual global EV sales are expected to climb to 25 million in a baseline scenario but up to 230 million a year in the most optimistic scenario (IEA, 2021).

Although the United States has abundant raw minerals, brines, and unconventional sources for lithium production, and to a lesser extent for cobalt and nickel, there is presently limited domestic production of these raw materials (Figure 1). In 2020, U.S. cobalt and nickel mine production represented less than 1% of global mine production, while lithium production came from a single brine operation in Nevada.[3] While there is some domestic production of lithium precursors, domestic production of nickel and cobalt concentrates are exported for processing for end-uses other than lithium-ion batteries (U.S. Geological Survey (USGS), 2021a).

The Secretary of the Interior has identified 35 mineral commodities as critical in the list[4] published in the *Federal Register* by the Secretary of the Interior (U.S. Department of Interior (DOI), 2018).[5] Of these 35 minerals, the United States was 100% net import reliant for 14 minerals, more than 50% import-reliant for 17 of the remaining 21 mineral commodities, and greater than 50% net import reliant for lithium, cobalt, and nickel in 2020 (USGS, 2021a). This import dependence can create risk in domestic supply chains, particularly when supply is concentrated in only one or two countries. For other critical minerals, the United States lacks downstream domestic and manufacturing capabilities, creating dependence further down the value-chain. These issues highlight the risk for supply disruption in critical minerals supply and value chains.

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[1] The term "electric vehicle" (EV) refers to battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and plug-in electric hybrid vehicles (PHEVs). The DOE Alternative Fuels Data Center (AFDC) contains an overview of the differences: https://afdc.energy.gov/vehicles/electric.html.

[2] EVs include passenger light-duty vehicles (LDVs) but exclude 2/3-wheelers.

[3] U.S. lithium production is withheld from the cited reference to avoid disclosing company proprietary data (U.S. Geological Survey, 2021).

[4] 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

[5] An update to this list is in progress. The 2021 Draft List of Critical Minerals was published in the Federal Register for public comment on November 19, 2021. See the draft list at: https://www.federalregister.gov/d/2021-24488.

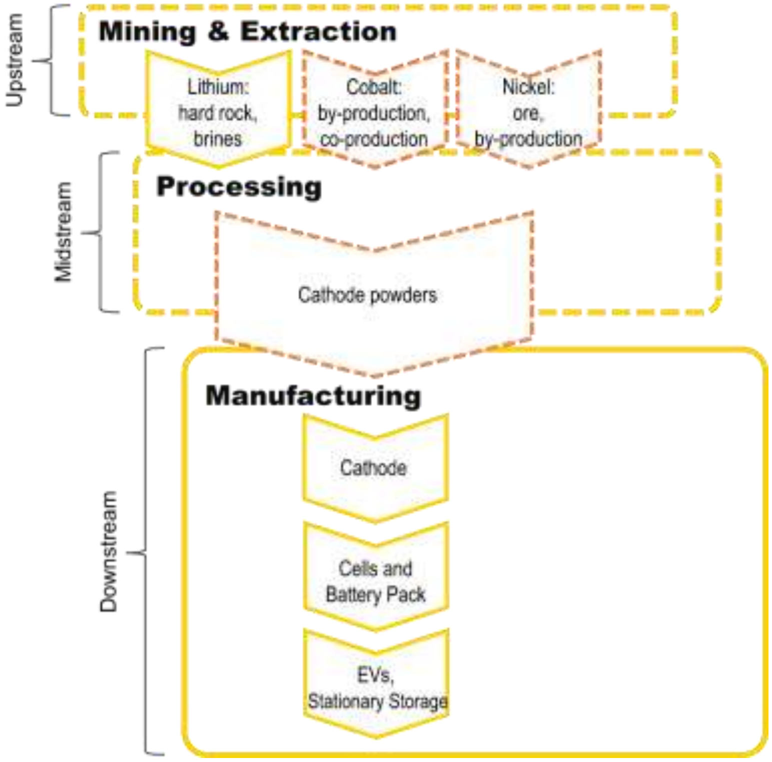

Figure 1. Domestic critical materials supply chain for lithium-ion battery cathodes.

Note: Items in yellow indicate some domestic capacity exists, while gaps on a globally competitive scale are indicated in orange.

Strategic Federal Response

On June 8, 2021, in response to Presidential Executive Order (E.O.) 14017, "America's Supply Chains," the White House released a report titled *Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth* (The White House, 2021b). The report identified risks in the supply chains for large capacity batteries, as well as critical minerals and materials, which are each paired with a set of policy recommendations to address these risks. Recommendations include but are not limited to:

- Establishing a Supply Chain Resilience Program.
- Investments to develop next-generation batteries to reduce or eliminate scarce materials including cobalt and nickel needed for EVs and stationary storage.
- Establishing a national lithium battery recycling policy including support for innovations to profitably recover and re-use key materials.
- Support for small, medium, and disadvantaged businesses in critical supply chains.

These policy recommendations provide a framework within which federal agencies and departments will advance initiatives to build resilient, diverse, and secure domestic supply chains.

E.O. 14017 recognizes the need for resilient, diverse, and secure domestic supply chains for both high-capacity batteries and critical materials. It builds on over a decade of investment and ongoing work across the United States Government to address critical material supply risks. This work includes a 2019 report titled *A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals* (U.S. Department of Commerce (DOC), 2019). As part of implementation of the Federal Strategy on Critical Minerals, the federal government is working to advance transformational research, development, and deployment across critical mineral supply chains. This includes developing a research, development, demonstration, and deployment roadmap that identifies ongoing activities and key needs to build resilient, diverse, and secure supply chains to ensure economic prosperity and national security of the United States.

The Department of Energy's Role

The U.S. Department of Energy (DOE) coordinates work across multiple internal technology offices and program to build resilient, diverse, and secure domestic supply chains for critical minerals and materials. As part of this work, DOE assesses minerals and materials 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 critical mineral and material research, development, demonstration, and deployment (RDD&D) around three core pillars in a safe, sustainable, and environmentally just way:

- Diversifying supply
- Developing substitutes
- Driving recycling, reuse, and more efficient use – including balancing co-production.

DOE's core RDD&D pillars are supported by system analysis; market and supply analysis; financing; user facilities across the Department's national laboratory system; criticality assessments; international collaboration; and collaboration with other U.S. government agencies and departments.

As part of interagency collaboration, DOE co-chairs the National Science and Technology Council (NSTC) Critical Minerals Subcommittee (CMS) with the U.S. Geological Survey (USGS) and the White House Office of Science and Technology Policy (OSTP). The NSTC CMS is the interagency body responsible for implementation of the *Federal Strategy to Ensure Secure and Reliable Supplies of Critical Materials* ("Federal Strategy on Critical Materials").[6]

As part of its umbrella framework to address key critical mineral supply chain challenges, there are six Calls to Action. DOE serves as the lead on the specific Call to Action to "Advance Transformational Research, Development, and Deployment across Critical Mineral Supply Chains." DOE leads this effort to include development of a federal RDD&D roadmap, but it does so in coordination with broad federal agency input.[7]

Collaborating Offices

DOE's RDD&D efforts address much of the supply chain for battery critical materials, ranging from resource assessment, through extraction and processing, to reuse and recovery at end-of-life. Key EERE activities are carried out by three technology offices within the DOE Office of Energy Efficiency and Renewable Energy (EERE), specifically, the Advanced Manufacturing Office (AMO), Vehicle Technologies Office (VTO), and Geothermal Technologies Office (GTO). The activities of each of these EERE technology offices are described in the sections below.

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[6] For more information, see the report *Critical Minerals and Materials: U.S. Department of Energy's Strategy to Support Domestic Critical Mineral and Material Supply Chains, FY 2021 – FY 2031*. This report is available at: https://www.energy.gov/sites/prod/files/2021/01/f82/DOE%20Critical%20Minerals%20and%20Materials%20Strategy_0.pdf (accessed November 16, 2021).

[7] Other key coordinating agencies of the NSTC CMS are 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).

Advanced Manufacturing Office

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 are as follows:

- Improve the productivity, competitiveness, energy efficiency, and security of U.S manufacturing.
- Reduce lifecycle energy and resource impacts of manufacturing goods.
- Leverage diverse domestic energy resources and materials in U.S. manufacturing, while strengthening environmental stewardship.
- Transition DOE-supported innovative technologies and practices into U.S. manufacturing capabilities.
- Strengthen and advance the U.S. manufacturing workforce.

In support of these goals as connected to critical materials for lithium-ion batteries, AMO funds lithium-ion extraction, as well as battery recycling and reuse R&D through the Critical Materials Institute (CMI), a DOE Energy Innovation Hub 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.

Energy Storage Grand Challenge [8]

AMO's activities also include the DOE Energy Storage Grand Challenge (ESGC), which was announced in January 2020. The ESGC mission is to be a global leader in energy storage innovation, manufacturing, and utilization. This mission is in support of the ESGC vision in which energy storage technologies enable a U.S. and global energy system that is resilient, flexible, affordable, and secure. Using an organized group of R&D funding opportunities, prizes, partnerships, and other programs, ESGC includes the following goal for the United States 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.*

Geothermal Technologies Office

Beyond the traditional value that geothermal resources can provide for electricity or thermal applications, there is a promising opportunity presented by tapping into geothermal brines for valuable byproducts including critical materials. Since 2014, GTO has supported R&D awards through two funding opportunities involving competitively awarded R&D solicitations focused on mineral recovery from geothermal brines through novel extraction technologies. GTO has also focused on developing better resource characterization methods 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 the details of process and performance are known only to intellectual property (IP) owners and operators (including pilot demonstrations partially funded by DOE).

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[8] 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 Energy Efficiency and Renewable Energy (EERE) and Office of Electricity (OE) and includes the Office of Science (SC), Office of Fossil Energy and Carbon Management (FECM), Office of Nuclear Energy (NE), Office of Technology Transitions (OTT), Advanced Research Projects Agency - Energy (ARPA-E), Office of Policy, the Loan Programs Office (LPO), and the Office of the Chief Financial Officer (CFO). Source: https://www.energy.gov/energy-storage-grand-challenge/about-energy-storage-grand-challenge (accessed November 15, 2021).

In March 2021, GTO launched the Geothermal Lithium Extraction Prize. The Prize consists of three phases focusing on the development of economic direct lithium extraction technologies from geothermal brines found in the Salton Sea / Imperial Valley area of Southern California. Each phase includes a contest period during which participants work to rapidly advance their solutions.

During Phase 1 of the Prize, competitors focused on forming teams lead by academic captains, with the option to partner with small businesses to form their ideas and concepts. During a six-month period, participants identified impactful ideas and concepts that aim to extract lithium more effectively from geothermal brines and improve on the state-of-the-art technologies while also reducing processing steps, water usage, and/or power consumption. Phase 1 concluded in September 2021 and the announcement of Phase 1 semifinalists is planned to occur in November 2021. The semifinalists will then advance to Phase 2 of the prize, focusing on advancing their technologies under the mentorship of an Industry Advisory Panel of leading industry experts in critical minerals extraction.

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. GTO 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 (DOE, 2020b).

Vehicle Technologies Office

The Vehicle Technologies Office (VTO) has a comprehensive portfolio of early-stage R&D to enable industry to accelerate the development and widespread use of a variety of promising sustainable 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 per kilowatt hour (kWh) in 2020 (Nelson et al., 2019). However, 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. But rapidly decreasing costs are associated with increased demand for battery materials for lithium-ion batteries. This causes fluctuation and uncertainty in the battery materials supply chain.

To mitigate potential lithium-ion battery supply risks, DOE has established the following goal: By September 2030, reduce the cost of EV battery packs to less than $60/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 three key complementary 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.

Among its other effort, VTO established the ReCell Lithium Battery Recycling R&D Center in 2019 to focus on recycling processes to recover lithium battery critical materials, and it launched the Lithium-Ion Battery Recycling Prize. The purpose of this prize is 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. Finally, VTO chairs participates, along with AMO, in the recently launched Federal Consortium for Advanced Batteries (FCAB) to connect federal agencies interested in establishing a domestic supply of lithium-ion batteries. Specifically, FCAB aims to accelerate the development of such a domestic supply of lithium-ion batteries by bringing together federal agencies having a stake in such an effort (DOE, 2020b).

Purpose of RFI and Workshop

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 battery materials supply chains. EERE was specifically interested in information on raw minerals production along with, the refining and processing of cathode materials including cobalt (Co), lithium (Li), and nickel (Ni) (The White House, 2021b). In the case of nickel, it was assessed as a critical material for high-capacity batteries (The White House, 2021b), and USGS recommended that it be included on an updated Critical Materials List (Nassar and Fortier, 2021). The RFI was issued by EERE's Advanced Manufacturing Office (AMO), in collaboration with its Geothermal Technologies Office (GTO) and Vehicles Technologies Office (VTO).

Based on the directives and RFI initial results, AMO, VTO, and GTO hosted an R&D Battery Critical Materials Supply Chain Workshop to determine opportunities, gaps, and bottlenecks in the battery cathode materials supply and value chain. The workshop was held on December 10, 15, and 17, 2020, and was driven by the goal to create a diverse, domestic battery supply chain in the next five years. Broadly, the workshop sought 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. Workshop participants focused on identifying impactful research and performance metrics for developing future pathways specifically for AMO/GTO/VTO, as well as, integrated across EERE's broader supply chain research efforts. This report contains the results of both the RFI and the workshop. It is not intended to be a comprehensive review of the domestic battery supply chain, but rather a reflection of input and discussion of the responses to the RFI and participants in the workshop respectively.

Workshop Summary

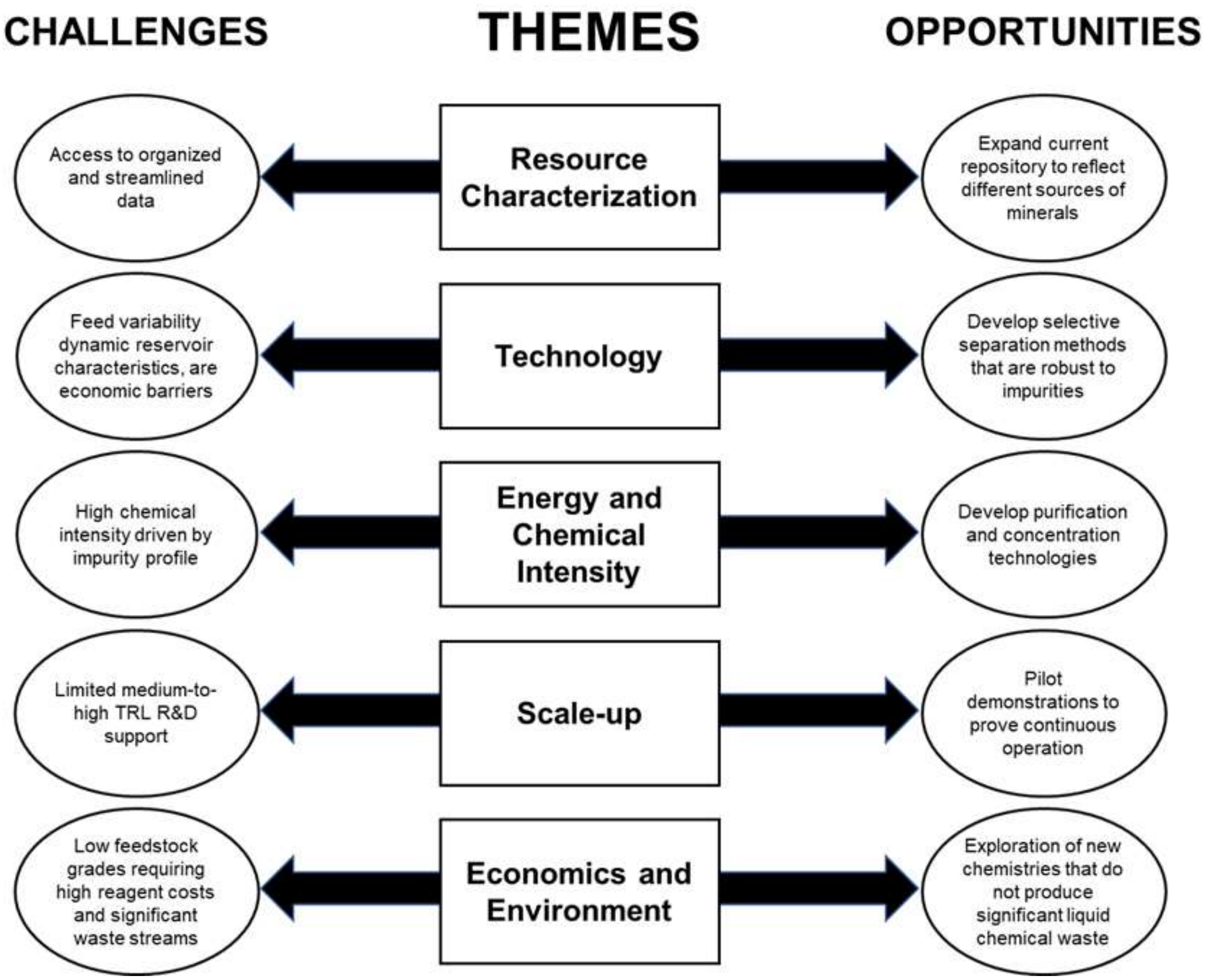
The workshop featured three days of focused discussion on lithium, nickel, and cobalt, as well as cathode manufacturing (see agenda in Appendix A). Each day included an opening presentation from DOE to frame the discussion, followed by extensive discussion sessions to review the key questions posed by DOE. The workshop employed an interactive brainstorming tool to facilitate anonymous polls and short answer Q&A sessions and solicit responses from active participants and key stakeholders. This input is informing the development of the R&D roadmap as part of implementation of the Federal Strategy on Critical Minerals and was integral to providing detail to the FCAB Battery Blueprint 2021–2030, which charts a federal government strategy to increasing the domestic battery supply chain over the next 10 years. This will also facilitate strategic planning and forecasting that will inform future directions in EERE programs to include R&D funding opportunities, prizes, awards, and partnerships.

The three-day workshop was attended by a total of 114 participants who were designated either as "active participants" or "observers." Active participants were primarily industry stakeholders that represented a key part of the supply and value chain for critical materials. This was to enable EERE to better understand the state of the industry, current and future challenges, and opportunities to address them. Observers included stakeholders from national laboratories and federal agencies that are also invested in advancing the critical materials supply chain. They were asked to be in listen-only mode during the workshop but were given the opportunity to provide feedback on the summary report prior to publication. To prepare for the facilitated discussions, a read-ahead document was distributed to the participants, which outlined DOE's preliminary findings from the RFI and the outstanding questions to be addressed in the workshop.

Key Takeaways

Graphical Summary

Below is a graphical summary of the results generated by the workshop. This graphical summary is intended to provide a high-level overview of key themes and associated challenges and opportunities. These themes and their challenges and opportunities are discussed in detail in subsequent sections of this report.



Polling Questions

The participants were polled during the workshop to engage the audience and introduce active learning and conversation modes for an interactive session. In addition, the poll questions also helped identify rapid responses to pertinent queries related to the workshop. Here are the key takeaways from the poll (additional details on the polls can be found in Appendix B):

- The participants identified that facilitating funding opportunities (for both early-stage research and development (R&D) and technology transition such as scale-up and demonstration/pilot activities) is the best use of government investment or federal programs that will strengthen U.S. manufacturing and recyclability and reduce dependence on foreign sources of critical materials (Figure 2).
- The main bottlenecks that the participants experience regarding lithium processing/manufacturing are due to immature and inefficient technologies for processing, separation, and purification.

- The greatest scientific/technical/engineering challenges to bringing domestic nickel and cobalt mining online include inefficient mature technologies and inadequate scale-up strategies for emerging technologies, as well as lifecycle and environmental challenges and potential changes in cathode chemistries.
- The results revealed that the key trends in the next 5–10 years related to battery materials will be declining lithium-ion prices and a transition to developing and utilizing newer cathode chemistries such as oxide cathodes (of nickel, cobalt, or manganese).

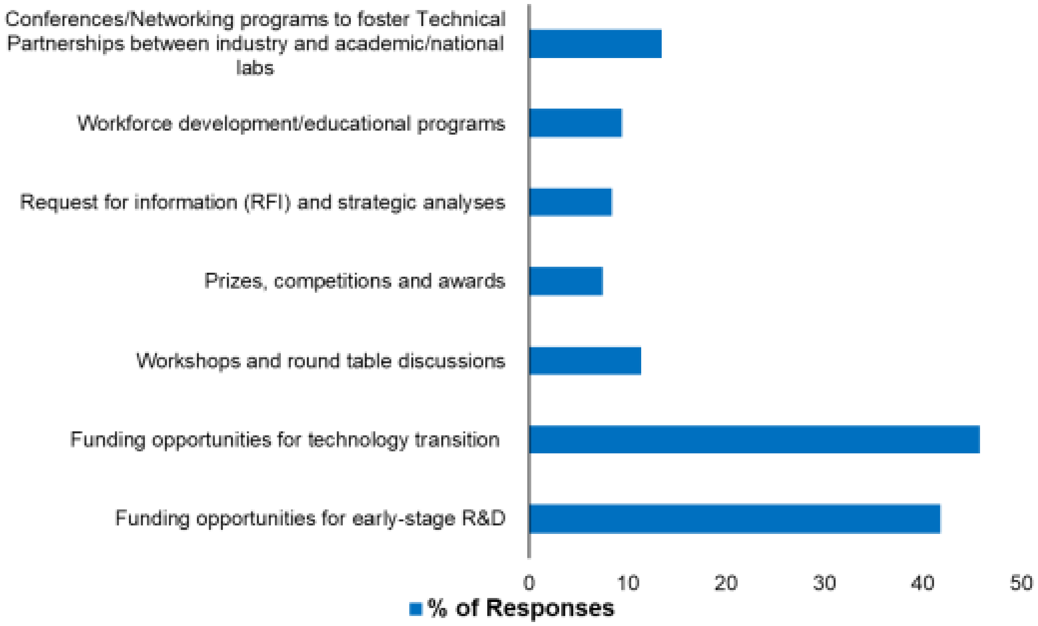


Figure 2. EERE R&D Battery Critical Materials Supply Chain Workshop – participant question 1 results.

Note: Summary of responses shown by percentage to question 1 by workshop participants regarding the best use of federal funds in support of critical materials R&D.

Qualitative Takeaways

Crosscutting Themes

The major themes from the Request for Information (RFI) and workshop are resource characterization, technology, energy and chemical intensity, scale-up, economics, and the environment. Crosscutting themes from the RFI and workshop discussion include the following:

- Industrial stakeholders emphasized the need for opportunities to validate technologies at the pilot scale. In this context, continuous operation is more important than the scale of the pilot plant.
- There is a need for increased connectivity across the supply chain.
- The participants agreed that ensuring supply security requires a strategy that prioritizes resource diversification. The United States depends heavily on foreign sources for these minerals and needs a dependable and formidable network to ensure a resilient supply chain.

Lithium

- Industry stakeholders identified limited federal investment into scale-up of mature technologies for separation and purification as a major challenge to increasing domestic sourcing of lithium (Li) from brine and hard rock resource. Consequently, the availability of U.S. Department of Energy (DOE) R&D funding to complement venture capital investments can go a long way to de-risk new technologies, reduce the cost of capital, and improve overall project economics. Funding for pilot test-bed projects—such as geothermal lithium extraction and recovery—will make it possible to prove emerging technologies against realistic conditions.

- Process intensification and energy integration can improve the energy and chemical intensity of lithium extraction. For instance, process designs that provide electrolysis power requirement from geothermal energy can improve both energy efficiency and environmental footprint of geothermal brine resource extraction.
- De-segmenting the lithium brine value chain can enable some degree of vertical integration from resource owners to technology providers. This will complement the development of scalable technologies suited to the lower grade brine resources in the United States.

Nickel & Cobalt

- The workshop participants agreed that ensuring supply security requires a strategy that prioritizes resource diversification. The United States currently depends heavily on foreign sources for these minerals and needs a shift in strategy to ensure a resilient supply chain. Given the anticipated growth in lithium-ion deployment for electrified transportation, it is also projected that secondary streams from end-of-life batteries could become a significant domestic source for nickel (Ni) and cobalt (Co). Therefore, funding opportunities for both early-stage R&D and high technology readiness level (TRL) technology transitions for both primary and recycled resource processing will strengthen U.S domestic manufacturing and reduce dependence on foreign sources of critical materials.
- Most known domestic resources produce nickel and cobalt as minor elements, and the economics of nickel/cobalt recovery depends on value recovery from other elements. Moreover, these resources often contain impurities in larger proportion than the nickel or cobalt (e.g., arsenic (Ar) in mine tailings), making separation and purification technically challenging. Thus, R&D directed at reducing processing costs – from pre-treatment to refining – can lead to economically competitive solutions. In addition, strategies such as co-location can eliminate transport costs and further improve economics.

Cathode Manufacturing

- The industry anticipates a shift towards nickel-rich cathodes in the next decade, accompanied by a corresponding transition towards cobalt-free chemistries. However, long-term agreements for cobalt supply, coupled with increasing lithium-ion battery demand might continue to make cobalt an important commodity for lithium-ion batteries. The industry expects new anode materials to include hybrid graphite/silicon, as well as anodes based on metallic lithium.
- There is value in clearly defining the purity requirements for different stages of precursor materials, along with which forms of impurities are more critical than others, as a step towards developing standards for domestic cathode manufacturing. This calls for basic research to determine and publish the required purity limits. It also requires understanding synergistic scenarios where impurities in one processing stage (e.g., metal purification) can be useful dopants in subsequent stages (e.g., cathode manufacturing).
- While lithium metal in solid-state batteries provides a compelling value proposition, the current market is focused on existing lithium-ion architecture, and without a clear demand for lithium metal foil, it is difficult to attract R&D investment. Moreover, the current production method is both expensive and energy intensive and generates a lot of waste. Industry stakeholders agreed that DOE funding could help benchmark early-stage technology performance, overcome key barriers, and de-risk future investment in technology scale-up.
- While the current market might not be willing to pay for the added cost of Environmental Social Governance, the increasing pressure on electric vehicle (EV) manufacturers to scrutinize the

environmental content of materials in their product could incentivize adoption of novel technologies with lower environmental footprints.

Lithium

***Note:** The content in this section represents direct contributions from the workshop participants, and where relevant, includes text from RFI responses that elaborate on participant comments. To provide context, each section contains sub-captions stating the question prompt to which participants responded.*

State of Industry

General Background

Global lithium (Li) reserves are estimated at 21 million tonnes with the United States accounting for about 3.5% of that total (Figure 3).[9] Batteries have been the primary driver for the recent growth in lithium demand and account for about 70% of end use applications (USGS, 2021a). While demand for lithium dropped by 5% between 2019 and 2020 due to the impact of Covid-19 and the resulting drop in electric vehicle (EV) sales, it is predicted to overtake supply by 2025, primarily driven by EV battery sales, which will drive investment in new lithium extraction technologies (USGS, 2021a).

The United States currently sources about 90% of its lithium from South America (USGS, 2021a). While South America has abundant brine-based lithium sources, Australia hard-rock lithium has captured most of the growing market. This is due, in part, because hard rock (spodumene) processing has lower technical risk – the technology is mature and can leverage existing infrastructure assets – and as a result, is less capital intensive. In addition, the ability to manage mine plans, stockpile raw material, and maintain consistent process feed conditions generally make spodumene processing easier to manage. Compared to hard rock deposits in the United States, workshop participants and Request for Information (RFI) responders thought that the remote location and abundance of hard rock lithium deposits close to established mining regions in Australia offer a more attractive investment proposition.

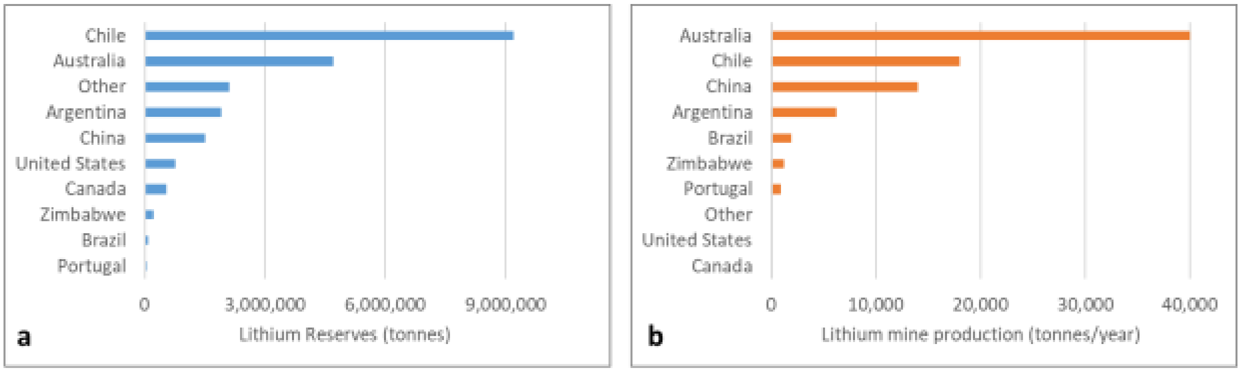


Figure 3. Lithium reserves and mine production data.

Note: Figure adapted from USGS, 2021a. Lithium reserves are in tonnes and mine production data are in tonnes per year.

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[9] The tonne is a metric unit of mass equal to 1,000 kilograms and is also known as a metric ton. The "tonne" is distinct from the English (Imperial) system unit of weight known as a "ton" that includes both a "long ton" and a "short ton." The long ton equals 2,240 pounds exactly while the short ton equals 2,000 pounds exactly. Using the conversion of 1 kg = 2.2046 pounds, 1 tonne equals ~0.98421 long tons and ~1.10231 short tons. Alternatively, 1 long ton equals ~1.01605 tonnes and 1 short ton equals ~0.90719 tonnes. The short ton unit is most commonly used in the U.S., and it is therefore sometimes referred to as the "U.S. ton." This report uses the unit of the tonne.

U.S. lithium deposits broadly include brine and hard rock sources. Brine sources account for 70 to 80% of total U.S. lithium deposits (Bradley, et al., 2017a) and include closed basin, lithium clays, oilfield brines, and geothermal brines, while hard rock deposits are primarily pegmatite sources (Figure 4). While brine sources are distributed across several Western states, commercially important hard rock reservoirs are located primarily in North Carolina (with concentrations of 800 to 4,000 parts per million (ppm)) and South Dakota (which contains one of the largest spodumene crystal varieties). In 2020, the only U.S. lithium production came from a brine operation in Nevada. Domestic production data were withheld to avoid disclosing company propriety data, but it is estimated to be less than 1% of the global total. In 2020, global annual mine production of lithium was about 82,000 tonnes per year (USGS, 2021a).

Figure 4. Lithium resources in the lower 48 U.S. states.

*Note: An * indicates the resource is currently not producing. Sources: Bradley, et al., 2017a; Bradley, et al., 2017b.*

Participant Comments

According to the workshop participants, technologies for extracting lithium from brine include multi-step precipitation, ion-exchange, solvent extraction, electro-dialysis, and membrane separation. Hard rock extraction typically involves comminution, high temperature calcination, extraction via acid roasting, leaching, neutralization, and impurity removal. State-of-the-art processes produce lithium carbonate (Li_2CO_3) as primary product, and then lithium hydroxide (LiOH) from carbonate, as needed. However, the industry trend towards higher energy density cathodes is increasing the demand for lithium hydroxide, making a case for direct (electrochemical) conversion from brine to hydroxide. Direct hydroxide production from brine can reduce process energy intensity and has been demonstrated at the pilot scale.

However, the participants noted that when considering the technical risk, permitting risk, uncertain operating costs, and generally higher capital costs associated with Direct Lithium Extraction (DLE) technology, the initial supply response of the lithium industry has favored traditional spodumene resources. Lithium demand is primarily driven by trends in current cathode chemistry, and more so by the current trend towards higher nickel content cathodes. The current industry standard requires up to 99.9% purity for lithium carbonates, but there is a possibility that lithium hydroxide purity requirements might be even higher. In the longer term (~10 years), the industry anticipates growth in demand for lithium metal/foil in the United States with the advent of solid-state batteries.

Challenges & Opportunities

Extraction

Resource Characterization

What value does improved lithium resource characterization in geothermal resources provide? What steps are needed to move beyond high-level regional assumptions?

The prevailing view in industry is that geothermal resource characterization is not an important barrier to resource development. The understanding of geothermal resources is relatively mature, as geologists, hydrogeologists, and petroleum engineers from industry and academia have heavily explored them for decades. Additionally, several datasets associated with ongoing geothermal operations exist. However, information from characterization of lithium concentration of geothermal brines in all geologically active areas and all operating geothermal power plants are not widely accessible. In particular, while much of the data are public, they are in disparate sources and are difficult to find and collate. Furthermore, while industry is good at identifying exploration targets, the limited development of geothermal resources remains process technology and finance related. The industry often lacks access to early drilling funds and incentives that help recover cost of exploration.

Therefore, collating the relevant characterization data, organizing data into usable forms, and then publicly releasing that data will allow technology/development firms to identify and engage brine suppliers and mineral right owners more directly and productively in pursuit of a path toward commercialization. When applicable, expanding characterization beyond geothermal resources will help de-risk project development and enhance the ability to pursue new and innovative lithium recovery technologies. On the technology side, developing processes that can handle brine from multiple sources can mitigate the effect of supply disruptions caused by geothermal plant required shutdowns for annual maintenance. The challenge with financing can be addressed by leveraging practices and financing mechanisms from the oil and gas industry that provide access to early drilling funds. Geothermal development requires an off-take agreement to attract funding to drill. Power off-take agreements or lithium offtake agreements are needed to promote funding for early drilling.

Technology

What are the greatest scientific/technical/engineering challenges to bringing domestic brine extraction online?

Key technical and science challenges identified by participants to bringing domestic brine extraction online include feed variability; dynamic reservoir characteristics; performance and economic barriers constraining extraction and processing technologies; and limited high technology readiness level (TRL) R&D support. Primary feed variability within and across reservoirs impacts the effectiveness of extraction/processing technologies, and it challenges adaptability for process flowsheets tuned for specific feed composition. In addition, limited data on physical and chemical reservoir changes (in response to lithium production) over time affects performance over processing lifetime. Key technologies identified by participants for direct lithium extraction include adsorption, solvent extraction, and ion-exchange. State-of-the-art sorbents show technical promise because of their ability to strip without using reagents. However, they are vulnerable to impurities such as manganese and iron, and they generally require further downstream purification, or upstream pre-treatment. Solvents have been developed that show excellent selectivity for lithium but given limited support for high TRL R&D to move technologies beyond pilot demonstrations, these technologies have not been evaluated at scale, and the economics remains highly uncertain. Ion exchange technologies likely hold the greatest promise in geothermal lithium brine recovery but face the same challenge of limited high TRL R&D support.

Opportunity exists to develop and advance extraction and processing technologies for brine resource, including developing highly selective sorbents that are robust to impurities, as well as novel solvents, synergistic extraction agents, and ion-exchange media with excellent selectivity for lithium. Systematic characterization of reservoir changes across production lifecycle can support the design of composition-flexible, adaptable, or source-agnostic flowsheets for lithium extraction, processing, and purification. Participants identified as key to breaking technology barriers providing full spectrum R&D support from low through high TRL to support moving technologies beyond pilot demonstration. Continued development of lithium extraction from clay deposits and reducing process steps – e.g., avoiding the roasting step – can bring down costs to levels competitive with global spodumene resource. Exploring co-production opportunities for existing mines can yield results in the short term – e.g., potential extraction of lithium as a by-product from established mines.

Energy and Chemical Intensity

What are the energy and chemical intensity reduction opportunities in lithium extraction?
Contributions from participants, as well as responses to the RFI, indicate that the chemical intensity associated with extraction of lithium from brines is driven by the impurity profile of the brine source – in particular, the ratio between magnesium and lithium. The energy intensity associated with extraction of lithium from brine resources is considered low primarily because most conventional processes utilize solar evaporation ponds for lithium concentration and contain a significant portion of impurity precipitation. However, net lithium recovery from these conventional processes is generally less than 50%; involves long processing times (~18 months); is vulnerable to environmental conditions (humidity, rain, etc.); and it generally has negative environmental impacts.

The extraction of lithium from an ore (most commonly spodumene) is a more energy intensive process. The comminution of the ore body itself consumes a lot of energy, and the spodumene ore must undergo a high temperature calcination step (to convert α-spodumene to β-spodumene), followed by extraction via an acid roast and leaching process, then neutralization, and removal of impurities. Spodumene extraction is also reagent intensive, comprises a multiplicity of unit operations – especially for indirect production of lithium hydroxide from lithium carbonate – and creates significant waste streams that must be appropriately disposed. Clay deposit extraction is water intensive, as water use is proportional to product purity specification: Higher purity specs require more bleeding and hence, higher water stress to replace the bled liquor.

There is an opportunity to improve the overall lithium extraction process at competitive capital and operating costs by developing novel brine purification and concentration technologies, as well as lithium extraction technologies, such as DLE technologies. Efficiencies in the use of reagents, energy, and water could be achieved via use of ionic liquids, electrolysis, as well as more robust and highly selective solvents that do not require stripping (e.g., lithium aluminum hydroxide). Chlorine (Cl) needed for hydrogen chloride (HCl) production could be extracted from naturally occurring chlorine in brines using an on-site chloralkaline plant. Electrification of mining fleet is a major opportunity to reduce overall energy intensity and life cycle emissions. DLE technologies perform well selecting lithium over monovalents such as sodium (Na) and potassium (K), but they struggle selecting over the divalents calcium (Ca) and magnesium (Mg) that often appear in the brines. This is a major technological hurdle that needs to be overcome.

Primary opportunities for energy and chemical reduction in the extraction of lithium from ores include development of novel extraction processes that reduce energy requirement (e.g., ambient temperature separation methods) and eliminate multiple pH adjustments or intermediate product formations typical in the current processes. Additionally, the major obstacle to solvents for lithium extraction is that they are very expensive. They perform well, but the cost is prohibitive and would require support in reducing the cost of chemicals. Process intensification strategies such as eliminating high temperature processes in spodumene extraction, pre-concentration, and in-situ leaching in lithium clay (hectorite) deposits can reduce energy intensity and simplify the overall extraction process. Detailed geologic mapping to explore reservoir mineral chemistry can facilitate process intensification and reveal opportunities for co-production or impurity handling.

Scale-Up

What is the tipping point to scaling from bench to pilot, or from pilot scale to commercialization?
DLE technologies have not proven to be lower cost than refined lithium production originating from Australian hard rock resources. Lab, bench, and pilot scale experiments have all indicated that low operating costs are possible, but there are numerous challenges in realizing these projected costs at commercial scale. Pilot demonstrations need to prove continuous operation and cyclic repeatability in realistic operating environments, as well as long duration stability in product quality. Other tipping-point considerations include end-to-end project economics, ability to leverage existing infrastructure (no radical changes in supply chain), and demonstration scale in the range of 5,000 to 20,000 thousand (kilo)-tonnes per year (KTPY). One manufacturer pointed to 1,000 hours of uninterrupted operation on flowing brine with vessels that are designed within a factor of 100 of the commercial scale as adequate technology demonstration.

Economics

What does the direct lithium extraction market envision as a competitive cost target, and when will U.S. producers achieve this target?
As in the case of scale-up, participants noted that DLE technologies have not proven to be lower cost than refined lithium production originating from Australian hard rock spodumene resources. Techno-economic projections based on pilot-scale data range from $5,000/tonne (adsorption-based recovery) to $4,000/tonne (ion-exchange process). Some more aggressive estimates have suggested numbers as low as $3,000/tonne. However, participants agreed that economics is a very complex issue and there are several competing factors that ought to be considered. Given that U.S. brine grades are lower than their South American counterparts, and that reagent costs are significant and unavoidable, the more realistic estimate may be between $4,000-$5,000/tonne. But with historical prices for lithium carbonate from spodumene at $6,000–$6,400/tonne, a $5,000/tonne cost-competitiveness may be constrained by the additional cost of capital and royalties, as well as other soft costs. It is also important to understand the impact of introducing a significant quantity of lithium from brines on the market: A price depression from oversupply could further limit economic competitiveness. On the other hand, production maturity will reduce project and technology risks, tilting the cost reward curve to benefit domestic production. The participants also noted that the reagents and labor costs are the major cost components for most processes. Incorporation of process automation into modern facilities should increase cost-competitiveness.

Environment

What are the key environmental impacts or considerations?
Spodumene extraction is reagent intensive and creates significant waste streams that must be appropriately disposed. As mentioned in the Energy and Chemical Intensity section above, water use in clay deposit extraction is proportional to product purity specification as higher purity requires more bleeding and hence higher water stress to replace the bled liquor. One approach suggested for reducing reagent (e.g., acid) footprint involves using carbon dioxide (CO2) captured from flashed steam to convert lithium hydroxide to lithium carbonate. Captured carbon dioxide could also potentially be used in place of acid to strip lithium from sorbent, thereby eliminating need for acid storage, handling, and waste disposal. In addition, electrification of mining fleet provides a major opportunity to reduce overall energy intensity and life cycle emissions.

Processing

Technology

What are the greatest scientific/technical/engineering challenges to direct conversion to lithium hydroxide?
Key technical challenges of direct conversion from lithium chloride (LiCl) to lithium hydroxide (LiOH) identified by participants include (1) trade-off between selectivity, throughput, and fouling required for effective membrane design; (2) membrane cost and degradation in the presence of reactive impurities; and (3) the energy intensity of the electrolysis step in geothermal brine extraction. Participants noted that there are

currently no commercial scale operations converting lithium chloride directly to lithium hydroxide, but the greatest opportunity resides in the development of an electrochemical process for the direct conversion of a lithium-bearing brine to a lithium hydroxide product without the intermediate creation of lithium carbonate. There are technical and economic challenges to this chemical route that could benefit from research investment, but this investment should not select a winner, but rather, accommodate "a system of possible solutions." Furthermore, a good understanding of the quality and composition of the raw material brine is an important factor in determining potential viability.

Energy and Chemical Intensity

What are the energy and chemical intensity reduction opportunities in processing of lithium carbonate from raw material sources and for conversion of lithium carbonate to lithium hydroxide?

In the conversion from the lithium obtained via the spodumene calcination / leaching process, the energy and chemical intensity is driven by the high-temperature decrepitating step, sulfuric acid use in roasting, crystallization, and drying of the sodium sulfate decahydrate ($Na_2SO_4 \cdot 10H_2O$) by-product, and the subsequent evaporation and crystallization to form lithium hydroxide monohydrate. The chemical intensity for the downstream conversion processes is driven by other key raw materials such as sodium hydroxide to get lithium hydroxide and sodium carbonate to get lithium carbonate. Opportunities exist to (1) reduce the calcination temperature for conversion of spodumene from alpha-phase to beta-phase; (2) reduce acid use by changing the acid roasting process to an alkaline process such as a soda ash pressure leach; and (3) eliminate sodium sulfate as a byproduct of spodumene to hydroxide conversion.

The addition of lime to lithium carbonate to produce lithium hydroxide generates a significant amount of calcium carbonate ($CaCO_3$) by-product. Opportunity exists for conversion of this calcium carbonate by-product stream to a calcium oxide (CaO) that could be recycled back to the reaction step, but this requires a trade-off evaluation between the cost of energy versus the cost of lime and by-product disposal. When sodium hydroxide (NaOH) is used to control pH for the adsorption process, metals such as iron (Fe) and manganese (Mn) precipitate out as suspensions in the liquid, fouling the medium. Use of novel adsorbents or other media can reject these precipitates, allowing them to be separated as sludge and re-injected into geothermal reservoir after acid treatment.

The conversion of lithium carbonate from a brine resource is relatively low in energy intensity, with the primary energy consumption coming from the transport and mild heating (60-90°C) of the brine, and the drying of the lithium carbonate product. Chemical intensity is driven by the further purification of the concentrated lithium-containing brine (e.g., using lime for magnesium reduction) and the precipitation of the lithium carbonate using soda ash. Efficiently recycling calcium carbonate can reduce the amount of calcium hydroxide that is consumed. This by-product calcium carbonate can also be utilized as a precipitating agent to remove magnesium ions (Mg^{2+}) impurities from brines. Innovations in concentrating lithium chloride (LiCl) or lithium sulfate (Li_2SO_4), such as reverse osmosis or forward osmosis, can reduce energy intensity compared to evaporation with steam or mechanical vapor recompression. New and improved electrolysis membranes have the potential to improve the current efficiency of the lithium chloride / lithium sulfate to lithium hydroxide conversion.

Scale-Up

What is the tipping point for next-generation technologies? At what scale does a technology need to be demonstrated?

Principal technical and engineering challenges for spodumene-to-hydroxide processing scale-up include (1) controlling uniform calcination within the process; (2) managing impurities build-up over long term; (3) achieving required impurity removal at scale; and (4) achieving hydroxide crystal consistency at scale. The key metric for demonstration must be continuous operation with realistic feed composition and operating conditions, and for sufficiently long duration to capture accumulation effects. The pilot plant must take the true feed stock from the mining or brine extraction plant (synthetic and "representative" feed stocks are not adequate). Demonstrations at up to one-tenth scales are desirable, although pilot projects sized across a spectrum of scales provide better assessment of scaling behavior and minimize uncertainty. Additional tipping point criteria should demonstrate core processes and co-product economics for realistic variations in brine composition.

Pilot operations should also demonstrate the total lithium recovery, provide emissions data (solid, liquid, or air emissions) such that these can be used for permitting processes, and demonstrate steady state behavior with full recycle. Without full and sustained recycle to allow accumulation of impurities, the final lithium carbonate or lithium hydroxide – water product will not reliably represent the composition of the commercial product and its performance in the final battery form. Achieving a full recycle requires equipment scale that will allow that to occur, but this equipment scale results in a cost of tens of millions of dollars.

Economics

Is direct conversion to lithium hydroxide economical and, if not, what barriers remain to achieve cost-competitiveness?

According to participants, techno-economic projections suggest direct conversion from lithium chloride is cost effective, but its cost effectiveness might also depend on location-specific risks such as cost of electricity, permitting restrictions, and both co-product and by-product management, as well as technology-specific risks like membrane degradation. Current projections based on pilot experience aim to come in under $4,000/tonne. But to reliably achieve this, current membrane technology needs to be improved to address lithium selectivity, back-migration of hydroxide, membrane stability, and resistance to fouling. Use of geothermal electricity to at costs below $50 per megawatt-hour (MWh) is also desirable.

Environment

What are additional environmental impacts or considerations?

Exploration of new chemistries that do not produce significant liquid chemical waste – such as lithium acetate (C2H3LiO2) – and the use of renewable energy sources could provide significant environmental benefits.

Nickel and Cobalt

Note: *The content in this section represents direct contributions from the workshop participants, and where relevant, includes text from RFI responses that elaborate on participant comments. To provide context, each section contains sub-captions stating the question prompt to which the participants responded.*

State of Industry

General Background

Global nickel (Ni) reserves are estimated at 94 million tonnes (USGS, 2021b) with Indonesia, Australia, and Brazil accounting for 60% of this value (Figure 5). For cobalt, the total reserve estimate is about 7.1 million tonnes, with the Democratic Republic of the Congo (DRC)[10] and Australia accounting for 60% (Figure 6). Mine production is also concentrated with Indonesia and Philippines accounting for over 40% of global nickel production, while DRC provides over 70% of global cobalt (Co). The United States contributes less than 1% of global production and reserves for either material.

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[10] The Democratic Republic of the Congo (DRC) is also sometimes referred to as "Congo-Kinshasa" in order to differentiate it from the Republic of the Congo ("Congo-Brazzaville").

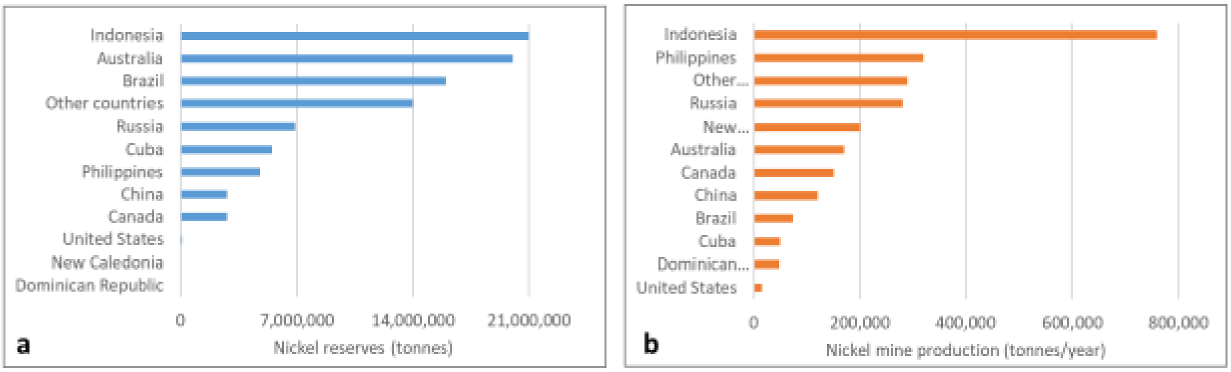

Figure 5. Nickel reserves and mine production data.

Note: Figure adapted from USGS, 2021b. Nickel reserves are in tonnes and mine production data are in tonnes per year.

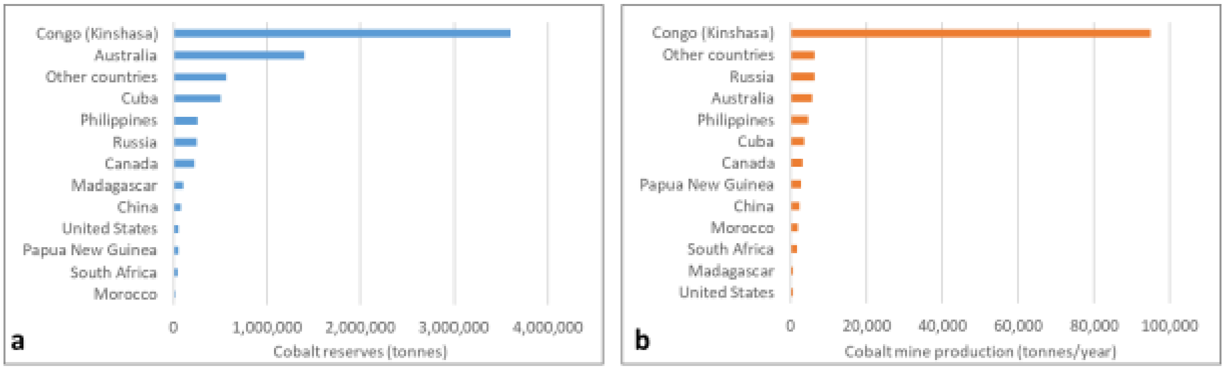

Figure 6. Cobalt reserves and mine production data.

Note: Figure adapted from USGS, 2021c. Cobalt reserves are in tonnes and mine production data are in tonnes per year.

In the United States, there is some nickel mining activity in the Eagle Mine project in Michigan, which produces about 16,000 tonnes of nickel concentrate (USGS, 2021b) and nickel recovery from mine tailings in Missouri (USGS, 2021b). The Tamarack Project in Minnesota is set to go into production as Eagle Mine winds down operations. There is also mining activity on lateritic deposits southwestern Oregon, estimated at about 13 million tonnes of ore with grade: 32.2% iron - 1.08% nickel - 0.107% cobalt (RNR Resources, 2020).

Participant Comments

With cobalt mining as primary product in the United States virtually non-existent, participants suggested that ensuring supply security requires a strategy that prioritizes diversity. This implies bolstering domestic supply with recycling, expanding access to global markets from reliable partners to includes Canada and Australia, and improving geopolitical engagement with countries such as DRC.

A broader issue with the nickel/cobalt supply security for the United States is that with limited local refining activity, concentrates from domestic mining need to be exported for further processing. Since the domestic source for class 1 nickel (post 2025) can meet some of the domestic demand from different end-use markets by supplying either concentrates or co-hydroxides to the downstream refinery, participants suggested that investing in all required stages of domestic processing could alleviate this reliance on the global stainless steel supply chain for domestic end uses.

In the short to medium term, access to nickel and cobalt from reliable partners (such as Canada) and geopolitical engagement with others (such as DRC) will help with supply diversification; in the long term, recycling would likely play a more important role in securing domestic supply but must meet purity specifications. Participants suggested that an initial step towards developing the domestic supply chain for nickel and cobalt could be an “industry baseline” study to understand (and share information about) the capabilities and landscape for domestic stakeholders in the industry, identify gaps, and assess where investment is likely to yield larger rewards for supply security. Additionally, tracking of critical materials will be key to understanding and addressing the entire scope of the supply challenge.

Challenges & Opportunities

Extraction

Resource Characterization

It is projected that in the medium-to-long term, secondary streams (recycled from end-of-life batteries) will be able to make significant contribution to domestic sourcing of nickel and cobalt. As for secondary stream processing technologies, the steps are similar to that for ore processing – filtration, leaching, extraction, precipitation, and electrowinning. However, recycled battery processing is typically more efficient because of higher concentration of nickel and cobalt in recycled streams compared to primary ore. More important challenges come from additives and binders, which are often more difficult to separate out. Since some of the same elements (nickel and cobalt) in the cathode also occur together in sulfide and laterite source minerals, the processes for their separation through solvent extraction are well understood. However, finding ideal solvents for the separations remains a useful goal, since no single commercial solvent is clearly superior. Recent literature has centered on synergistic solvents, where two or more extractants are combined to yield improved separations; in this way, effective synergistic solvents can lead to breakthrough performance. The typically smaller scale of recycling processes allows for improvements in equipment design, process intensification, and waste minimization when compared with primary mining and recovery.

Technology

What are the greatest scientific/technical/engineering challenges to bringing domestic nickel and cobalt mining online?

Key technical and science challenges identified by participants to bringing domestic nickel and cobalt mining online primarily relate to the difficulty with accessing remote resources and separating minor components. There is potential to expand nickel resources by improving geophysical survey methods and integrating advanced data analytics and machine learning to analyze geological data. Many of the known cobalt-containing resources have cobalt as a minor element, or they contain problematic impurities like arsenic (Ar), often in larger proportions than the cobalt. The technical challenge – and economic burden – of recovering cobalt from mine tailings is therefore compounded by the high arsenic concentration. Continued applied research and pilot scale projects are required to demonstrate technical and economic viability of cobalt extraction from these sources. There is also a need to understand purity requirements imposed by battery manufacturing specifications and, as well as the required purity specifications for precursor materials. Since impurity removal requires different processes for different groups and individual impurity elements, research and development (R&D) can determine – and document – the importance of different types/forms of impurities at different stages of the manufacturing supply chain from extraction concentrate to cathode precursor material.

What are the challenges in achieving more nickel refining in the United States?

To unlock more domestic nickel refining, the United States needs to secure access to nickel concentrates or intermediates and/or responsibly explore domestic mines. The challenge with expanding domestic production is that current prices (much greater than $20/kg) do not support investment in new mining and processing facilities. High quality deposits are rare, and since processing and refining techniques are complex and energy intensive, the high capital investment and permitting costs for small-scale, low-grade ore make nickel refining expensive. Domestic deposits will likely be insufficient to meet future demand for nickel in electric vehicle (EV) batteries (USGS, 2021b; Statista Research Department, 2018). As a result, the United States may increasingly depend on imports for nickel refining feedstock (e.g., sulfide ores from New Caledonia), which adds to the cost of refined products.

Because nickel processing is vertically integrated and located outside the United States, an effective solution must address the supply chain challenge and leverage technology innovation to reduce process economics. Developing a fully integrated material supply chain from ore to finished products, which includes domestic refining and conversion to sulfates, can reduce barriers to domestic refining. Moreover, technological innovation towards process intensification can reduce overall costs. For example, deep eutectic solvent technology can eliminate traditional solvent extraction stage, resulting in a more compact, cost-effective plant.

Energy and Chemical Intensity

What are the energy and chemical intensity reduction opportunities in extraction and processing of cobalt and nickel?

A potentially effective strategy for reducing energy intensity is co-location, which limits long-distance transportation to high value products. Concentrates generally contain about 10% of the target product by mass. The current approach of transporting concentrates means carrying nearly 90% waste over several miles to the smelter, which is wasteful. Also, the nickel matte from smelter contains only about 50% nickel, which highlights a further opportunity for reducing transportation cost by collocating upstream processes up to precursor production. Furthermore, the current supply chain for nickel matte takes it to smelters and then to nickel sulfate facilities abroad before being shipped back to the United States as product. Going from ore concentrate to cathode material via a local, integrated process provides a unique opportunity to reduce energy and chemical intensity.

Smelting is a very energy intensive process with large carbon footprint, and alternative renewable energy sources (e.g., solar thermal or biomass fuel) can significantly reduce carbon emissions. Furthermore, waste heat and steam recovery and reuse within smelting and refining process can reduce its energy intensity. Another option involves using hydrometallurgical processing routes that eliminates the smelting step. Other process upgrade and intensification options that can be achieved via directed R&D include redesigning to recycle water run-off from material processing and eliminating the tailings dam. Improving geological survey methods by leveraging artificial intelligence (AI) and data analytics will improve characterization and help streamline process design.

Scale-up

What are the tipping points for scaling up of next-generation technologies?

Like the case for lithium, pilot scale projects need to demonstrate continuous, cyclic, and repeatable operation in a realistic environment. Given the expectation that recycling is set to play an increasing role as feedstock in the medium-to-long term, demonstrations should also show the ability to flexibly adapt to feeds from nickel concentrates and recycled materials and handle mixed-feed streams. For primary mining, the suggested minimum scale for demonstration would be 10,000 tons/year, and for recycling, at least 1,000 tons/year.[11]

Economics

What economic barriers limit cost-competitiveness?

Economics and complexity involved in converting concentrate to battery-grade sulfate is uncertain. At the level of the mine, cobalt, and sometimes nickel (which is also a primary product), are often by-products of mining operation, and economic viability depends on the entire portfolio of primary mining products and by-products. Moreover, the current nickel supply for local battery manufacturing relies on the global stainless steel supply chain. Creating a complete supply chain from ore to finished product in the United States would

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[11] The type of ton referenced in response to this question – i.e., metric ton (tonne), short ton, or long ton – was not specified by workshop participants. Refer to footnote 9 for more information on these units.

eliminate costs that would otherwise be added by shipping overseas for processing. Furthermore, co-location eliminates costs associated with transporting non-target materials (and waste) in concentrates and mattes.

Environment

What are the key environmental impacts or considerations?
Several of current extraction strategies are reagent-intensive (e.g., high pressure acid leaching (HPAL) for laterite ores), and rely heavily on acid separation and precipitation, which release large quantities of toxic waste. Acid mine drainage can cause significant ecological damage, and mine tailings are difficult and costly to process and dispose. Development of near-zero discharge processes, as well as technologies like advanced dry-stacking with carbon dioxide (CO_2) sequestration, or in-situ leaching can minimize disposal and life cycle impacts. Mining residues can be explored for alternative uses such as supplements for concrete or asphalt production. There are R&D opportunities to improve water recovery from spodumene tailing. The geographic location of brine resources—e.g., the Salton Sea area—creates significant stress on the scarce, local water sources. R&D projects aimed at developing more efficient water use strategies for processing and cooling can help the overall development of lithium recovery from geothermal brine.

Processing (Conversion to Sulphates)

Technology

Is it desirable to design processes capable of handling multiple feedstocks such as raw and secondary materials? What are the processing challenges for cobalt arsenide deposits and for achieving more nickel refining in the United States?
The participants noted the desirability of designing processes capable of handling multiple feedstocks since this creates the future opportunity to gradually replace depleted mine resources with recycled materials to maintain or expand total production. However, this also introduces significant complications since specific processes are feedstock-sensitive and may not be robust to much variability. In general, combined material streams add to flowsheet complexity. While technologies such as smelting are more flexible to feedstock variability, hydrometallurgical processes are very sensitive to feed variability, imposing limits to recycled material penetration. Each feedstock introduces a different set of impurities (e.g., aluminum (Al) and copper (Cu) contaminants), and therefore, need different environmental handling strategies. Another challenge to feasibility of mixing feedstocks is the lack of clarity in exact purity/impurity specifications for both final and intermediate products. This requires communication between stakeholders to include battery manufacturers, mining companies, and recyclers.

Other challenges include the environmental and health hazards of arsenic and sulfide releases during ore extraction – for instance, processing may require high temperature roasting and high pressure leaching to eliminate arsenic. R&D could improve current methods for removing arsenic (like floatation during ore dressing or adsorption and solvent extraction during refining) and develop alternative methods such as selective solvent systems with favorable electrochemical properties that facilitate electrowinning.

Scale-up

What is the tipping point for next-gen technologies? (Scale of demonstration? Material qualification? Impurities?)
Scale-up studies require a fully integrated pilot plant that demonstrates (1) domestic self-sufficiency by taking domestically produced nickel concentrates through to nickel sulfates and/or refined nickel powders; and (2) continuous operation over a sufficient period to ascertain steady state purity, impact of circulating stream, robustness to variations in feed composition, and ability to remove detrimental impurities. While demonstration at scale is desirable, small-scale demonstration with continuous operation is better than large-scale batch operation.

Economics

What is the largest cost driver for battery-grade precursor production?
The cost drivers for nickel and cobalt processing are primarily associated with the high capital investment needs, pretreatment requirements, and process inefficiencies. U.S. deposits are limited, and since processing techniques are complex and energy intensive, small, low-grade ores make nickel refining expensive and energy intensive, as well as dependent on co-products for economic feasibility. Pretreatment requirements prior to separation and purification constitutes one of the biggest cost drivers for economic viability. Separation and purification also add significant costs, as components such as copper, iron, aluminum, and zinc need to be separated out. R&D can focus on the purification of intermediate products or leach streams to facilitate production of battery-grade precursor products.

Furthermore, the current processing includes several steps from concentrate to matte to briquette to sulfate to precursor materials. Some intermediate steps are avoidable, and R&D that reduce or eliminate intermediate steps will reduce costs, not least by eliminating intermediate transportation. For instance, deep eutectic solvent technology can eliminate traditional solvent extraction stage, resulting in a more compact and cost-effective plant. In-situ leaching can reduce mine development and reclamation costs by eliminating the need to excavate ore. However, care should be taken to avoid toxic or expensive leaching agents. Additionally, incentives that target new mine development costs – e.g., exploration, permitting, etc. – as well building out integrated domestic supply chains that avoid current global supply chain costs could also improve economics.

Electrode Manufacturing

Note: *The content in this section represents direct contributions from the workshop participants, and where relevant, includes text from RFI responses that elaborate on participant comments. The workshop discussion focused on cathode manufacturing, which is the focus of this section. The RFI included anode manufacturing and a summary of those response are included in this section as well. To provide context, each section contains sub-captions stating the question prompt to which participants responded.*

State of Industry

General Background

Increasing demand for electric vehicles (EVs) has imposed further strain on the supply security of cathode active materials critical to U.S. battery manufacturing. Given the current vulnerability of cobalt supply, and the danger of a global supply deficit by 2025 (McKinsey & Company, 2018), the industry expects a shift towards "low-cobalt" or "cobalt-free" chemistries, although the latter will require the realization of significant investments. Despite the decrease in the cobalt fraction within the cathode, overall cathode production will increase, resulting in a slower decline in the demand for cobalt. Lower cobalt fractions also mean a trend towards nickel -rich cathode chemistries. To meet the growing demand for batteries, industry seeks a strategy that will improve supply security and reduce associated supply chain costs. Such a strategy will facilitate the anticipated growth in domestic cathode manufacturing infrastructure.

Participant Comments

Stakeholders do not anticipate current lithium (Li) – nickel (Ni) – manganese (Mn) – cobalt (Co) oxide ("NMC") cathode chemistry to change considerably. However, a move towards nickel-rich cathode compositions (in which state-of-the-art nickel rich catholic composition is denoted NMC 6-2-2) and solid electrolytes is considered likely. This is due to factors such as concerns about cobalt sourcing and design needs for higher energy density and longer cycling stability. But nickel-rich chemistries require a greater supply of battery-quality nickel, and this would lead to greater competition for nickel with metal alloy manufacturers. Sodium (Na) and potassium (K)-based cathode chemistries are also of interest but over a longer research and development (R&D) timeline. Anodes are expected to shift to a combination of graphite and silicon (Si)-based or lithium (Li) metal-based compositions.

The industry does not have a uniform set of purity requirements for cathode materials. These vary by end-use storage application, source of the material (e.g., lithium hydroxide (LiOH) vs. lithium carbonate (Li_2CO_3), 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 parts per million (ppm). Magnetic impurities pose the greatest challenge, with an impurity tolerance as low as 1,000 ppm. The location of impurities is also important: Impurities on the surface of the electrode can hinder manufacturing and performance, while some impurities in the bulk are known to enhance structural stability and cycle life.

Challenges & Opportunities

Future Battery Chemistries

What cathode materials are likely to be used in the near to mid-term?
Industry participants expect oxide and cobalt lean/free cathodes to trend in the near term, although longer-term agreements between automakers and cobalt miners might mean that cobalt may stay in some form for the next decade. It is likely that nickel-rich cathodes would be adopted in pure electric vehicles (EVs), while mild hybrids, smaller EVs, and other applications would continue to use current lithium-iron-phosphate (LFP) and lithium-nickel-manganese-cobalt-oxide (NMC) chemistries. A shift to higher nickel content cathodes would require more lithium hydroxide. However, trends towards high-nickel chemistries could drive up prices of nickel, and the feedback effect might cause a shift back to the lower nickel (622/532/LFP) chemistries. However, price dynamics of nickel are hard to easily predict since nickel is mined as a co-product. There is also potential to explore manganese-rich chemistries, but questions about cycle life and capacity would need to be addressed before this is a viable technology option in the mid-term.

What anode materials are likely to be used in the near to mid-term?
Industry expects new anode materials to likely include hybrid graphite/silicon anodes and anodes based on lithium powders, foils, and films. The electrolyte is likely to remain lithium carbonate-based, but solid-state electrolytes may gain some market share in next five years. Solid state electrolytes may also eliminate need for coated plastic separators.

Pre-lithiated silicon oxide (SiO)-graphite anodes (less than 10% silicon content) are seeing greater interest and R&D from original equipment manufacturers (OEMs). Battery OEMs are actively looking for a safe and cost-effective solution that is compatible with today’s commercial electrode manufacturing processes. Specifically, materials stable in ambient air and compatible with today’s aqueous anode manufacturing processes are desired. Introducing lithium into the anode is a desired approach to offset the lithium lost to side reactions, thus preventing the lithium from the cathode being consumed during battery formation and thus increasing energy density. Pre-lithiated silicon-graphite anodes have two to three times higher capacity than silicon oxide-graphite anodes, but this area requires more research.

Lithium-metal anodes, which also have significantly higher capacity, could see technological maturity by 2025 based on significant OEM interest. The market for battery grade lithium metal for rechargeable batteries is expected to grow quickly and exceed today’s combined markets for primary batteries and non-battery applications before 2030. Lithium-metal anodes could work with solid state electrolytes, as well as conventional electrolytes with appropriate additives. However, more research in this space is needed, specifically on novel solid and liquid electrolytes; anode coatings; and cell design to improve coulombic efficiency and reduce the amount of inactive lithium formation. Additionally, lithium sulfur (Li-S) was highlighted in the workshop as a cost-effective alternative to existing commercial lithium-ion chemistries.

Cathode Manufacturing

Technology

Beside co-precipitation, could other processing methods be viable for future cathode production?
Co-precipitation has been demonstrated as a scalable, high quality, and cost-effective way to synthesize precursor materials. However, it needs two steps to convert raw to final cathode: A precipitation reaction to synthesize precursor followed by the combination of precursor with lithium to create the final product. Comparing the cost of precursor production to cost of the cathode, the conversion from precursor to final product is considerably costlier than the co-precipitation reaction. As such, finding a low-cost method to convert precursor to the final product might yield a greater cost advantage. Alternatives to co-precipitation could include low-cost continuous approaches that avoid contact with the container walls while hot; solvothermal processes; and solid-state reaction of atomically mixed starting precursors. Alternatives to roller hearth kilns could reduce capital cost, reduce calcination temperatures, and allow shorter calcination times that result in higher throughput for cathode production.

At what purity levels are powders for cathode materials considered battery grade? How are impurity studies performed?
Currently, no industry standard exists on purity levels and testing. OEMs test for impurities according to their own knowledge, experience, and requirements. For lithium carbonate, 99.3% lithium carbonate is generally considered battery grade, but 99.5% purity is a common battery grade specification for lithium carbonate produced from spodumene. For anhydrous lithium hydroxide, 99.5% lithium hydroxide is a typical battery grade specification. However, there appears to be a lack of data-driven basis for these limits. There is a need to understand what the likely impurities from domestic sources for lithium, nickel, and cobalt would be, followed by basic science studies to understand how much of these impurities are tolerable to derive standards for domestic cathode manufacturing. Battery performance parameters such as energy density, cycling stability, and cost need to be measured with several purities of starting chemicals.

Some impurities are more critical than others, but it's not always clear which or why. Magnetic and electrochemically active elemental impurities such as chromium (Cr), iron (Fe), zinc (Zn), sulfur (S), and chlorine (Cl) are considered the most problematic to cathode manufacturing. The location of these impurities in the cathode is critical. If they reside on the surface of the cathode, they can negatively impact electrode processing and/or solid electrolyte interphase (SEI) formation on the cathode. However, if they are incorporated (doped) into the cathode’s crystal structure, many of these “impurities” have been reported to enhance structural stability, cation ordering, power performance, and cycle life. It may be that consistency of impurity levels is more critical than reducing these levels to a specific quantity.

Higher nickel content has led to higher nickel purity requirements. Industry asserts that differences in impurities below ~500 parts per million (ppm) are difficult to discern, and techniques such as inductively coupled plasma mass spectrometry (ICP-MS) may be needed to measure low impurity concentrations. Trace impurities are commonly quantified via inductively coupled plasma optical emission spectroscopy (ICP-OES). In addition, chloride (Cl^-) and sulfate (SO_4^{2-}) anions are commonly determined via techniques such as ion chromatography (IC), turbidimetry, or ultraviolent-visible (UV-Vis) spectroscopy. Novel approaches in cathode manufacturing that allow use of low-purity nickel without sacrificing cycle life and energy/power density (e.g., using coatings or dopants) could potentially mitigate the need for high-purity nickel. Varying nickel purity would also be a factor to address in nickel obtained from secondary sources.

How important is collocating fabrication facilities near raw materials or refining sources?
While proximity between raw-materials sources, cathode manufacturing facility and battery/cathode recycling facility would be ideal, it is not regarded as a must by industry. Co-location may help ensure consistent quality, chemistry, and process in each of those facilities. Typically, industries produce precursor materials close to raw materials or sources since transporting sulfates with low metal content is costly. Another benefit of co-

location is a lower carbon dioxide footprint from transportation, which may be an important consideration for automotive OEMs.

Today, little to no cathode production occurs near the source of lithium raw materials, which are sourced almost entirely from Australian spodumene and Chilean brine. However, cathode producers are frequently located in proximity to battery producers, who source most of their cathode materials domestically. Currently, cathode materials are produced largely in China (42%), Japan (33%), and South Korea (15%) (Federal Consortium for Advanced Batteries (FCAB), 2021).

How many sources does a battery material producer need to supply a Gigafactory-scale production? Is multi-source qualification an issue?[12]

For most manufacturers who do not have a vertically integrated supply chain, multiple material sources are desired. A typical sourcing mix could be two or three tier 1 lithium suppliers, each sourcing from two to four lithium sources for each conversion plant in the value chain; one to three nickel suppliers with nickel originating from one or two nickel sources; and one or two cobalt suppliers with cobalt originating from one or two cobalt sources. A production capacity of 3 to 10 kilotons per year (KTPY) is expected for a supplier to qualify as a reliable source, although consistency in quality of delivered material is also key to qualification as a source (and the size of company may also be a factor). Manufacturers may additionally de-risk their supply by sourcing from recycled streams. Flexible process configurations that accept feeds from multiple sources and with varying compositions could also provide additional supply security.

Gigafactory scale battery production will generally utilize two or three individual sites producing cathode material, which in turn prefer to get no more than 30% of their supply from a single source. Material capacity availability and build up plans tie in with this exercise. A factor of 1.35–1.5 can roughly estimate the usage of raw materials in kilotons (kt) per Gigawatt-hour (e.g., a gigafactory with 10-GWh capacity would need 13.5 to 15 kt of cathode active material).

At what scale does diversification of material sources become economic for lithium, nickel, and cobalt powder manufacturers?

Most large cathode producers source their lithium salts from multiple lithium converters/refiners. This is driven more by price than availability, as large lithium converters produce enough material to be the sole supplier to several cathode producers. Five to ten kilotonnes per annum (ktpa) powder capacity usually seen as the threshold for increasing material source diversity.

Considering materials required for the production of 1 kg of cathode material, the amount of raw material needed is in the decreasing order of nickel > lithium > cobalt > aluminum by weight, and it requires a customized strategy to understand each metal market. Due to the nature of the metal market, it is difficult to predict prices, so long-term contracts are not always an advantageous option. In fact, contract flexibility may be viewed more favorably than contract length.

Deposit mineralogy, processing method, resource size, and proximity to infrastructure are the key drivers to enable a mining operation to be low-cost, as these factors insulate operations from market price swings and allow cost competitiveness even in low price environments. For a mining project to obtain financing, companies tend to prefer long-term offtakes with some portion at fixed prices to guarantee revenues while holding the remainder at market prices to retain exposure to underlying supply/demand fundamentals.

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[12] The type of ton referenced in response to this question – i.e., metric ton (tonne), short ton, or long ton – was not specified by workshop participants. Refer to footnote 9 for more information on these units.

Lithium Foil/Metal

Technology

The value proposition for lithium metal in solid state batteries of the future is substantial, but the pathway there is not clear, especially since there is currently no preferred architecture or winning technology. There is a need for early-stage technology performance for benchmarking. The key challenge with lithium foil production is the high purity specification required to avoid dendrite formation. Manufacturers need a clear spec sheet to understand tolerance for different types of impurities in lithium precursors.

Inorganic solid-state electrolytes with excellent ion conduction selectivity have much higher lithium transference numbers than traditional liquid electrolytes and enable higher cathode loading in high energy density cell design. Lithium salts are required to produce promising solid electrolyte candidates such as sulfide-based, oxide-based, and polymer-based solid electrolytes. Thinner forms of lithium metal, with thicknesses less than 20 microns (μm) will be needed to further optimize energy density, and surface treatment of the lithium foils will be needed to improve shelf life and extend cycle life.

Energy and Chemical Intensity

The current metal foil production method is expensive, energy intensive, and produces a lot of waste. It is therefore important to reduce the cost of the enabling technologies above to become competitive with today's lithium-ion costs. This includes lowering the cost of making lithium metal, manufacturing wide ultrathin lithium anodes, lithium deposition technologies, coating technologies, new electrolyte salts, and practical solid electrolytes. Many of these require economies of scale to be competitive.

Economics

The current market is focused on existing lithium-ion architecture, and without a clear demand for lithium metal/foil, it is difficult to attract R&D investment. The lack of reliable analysis of market projections reduces investor confidence within typical investment timescales. So, while growth in demand for solid-state batteries is likely, the timing and architecture of the winning technology remains highly uncertain.

Supply Chain

Which battery component materials are likely to face domestic supply challenges in the short term (1–3 years) and medium term (3–5 years)?

The lack of meaningful mining and processing of intermediates for all battery materials could be viewed as problematic from a supply chain vulnerability perspective. Cobalt and graphite are likely to have supply vulnerabilities in the short and medium term. Some see lithium supply as also being problematic in the near future since it has no substitute, nor can its use be meaningfully reduced in current formulations. Nickel is also at risk of shortages in the near future. There is currently no nickel mining and/or battery-suitable processing at scale in the United States, and, as such, the United States relies exclusively on imports for battery-suitable nickel. Battery-grade aluminum for prismatic pouch cells might also experience supply challenges in the medium term.

What other rapidly growing competing uses for nickel, cobalt, or lithium have the potential to disrupt supply for battery manufacturing?

Nickel demand for alloys in construction, automotive, machinery, and aerospace and defense applications could compete with nickel demand for batteries. Nickel is also used for catalysis and organic synthesis.

Cobalt demand for use in magnets and alloys could increase substantially due to the large growth expected in magnets/data storage devices and superalloys. This could certainly disrupt supply for battery manufacturing. Cobalt may also be used in the future in significant quantities for hydrogen electrolysis. Cobalt compounds are also used in lubricants, catalysts, biotechnology, and medicine.

Lithium appears to be relatively safe in terms of competing demand. Small quantities of lithium are used in the manufacture of aerospace alloys and Gorilla Glass, which may result in some competing demand.

Next Steps and Opportunities

As the part of the implementation of the Federal Strategy on Critical Minerals, a federal research and development (R&D) roadmap will be developed that will incorporate results from this and other workshops used to convene stakeholders across sectors and supply chains.

As described in the "Notice of Guidance for Potential Applicants Involving Critical Minerals and Related Activity," issued by the U.S. Department of Energy (DOE) Loan Programs Office, eligible critical minerals projects can consider applying for assistance under Title XVII or the Advanced Technology Vehicles Manufacturing (ATVM) Statute (DOE, 2020b).

DOE will continue to coordinate and collaborate with stakeholders to address the supply chains risks identified in the White House report released in June 2021 titled *Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth* (The White House, 2021b) and will help implement the National Blueprint on Lithium Batteries.

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Appendix A: Workshop Agenda

The workshop was hosted by the following U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) technology offices: Advanced Manufacturing Office (AMO), Geothermal Technologies Office (GTO), and Vehicle Technologies Office (VTO).

EERE R&D Battery Critical Materials Supply Chain Virtual Workshop

December 10, 2020

AGENDA

Please note that meeting times for topics each day are approximate and may be adjusted based on discussion during the meeting.

DAY 1: December 10th – Lithium

12:00 PM – 3:00 PM EST

Time	Activity
12:00 PM – 12:05 PM	**Welcoming Remarks and Introductions**
12:05 PM – 12:25 PM	**U.S. Department of Energy Summary**
12:25 PM – 1:40 PM	**Concurrent Breakout Sessions: Lithium** ○ Breakout Session 1: Lithium Extraction from Brines ○ Breakout Session 2: Lithium Extraction from Hardrock
1:40 PM – 2:20 PM	**Refinement of Raw Materials – Conversion to Lithium Hydroxide**
2:20 PM – 2:55 PM	**Refinement of Raw Materials – Production of Lithium Foil/Metal for Next Generation Batteries**
2:55 PM – 3:00 PM	**Wrap up and Closing Comments**

December 15, 2020

AGENDA

Please note that meeting times for topics each day are approximate and may be adjusted based on discussion during the meeting.

DAY 2: December 15th – Cobalt and Nickel

12:00 PM – 3:00 PM EST

Time	Activity
12:00 PM – 12:05 PM	**Welcoming Remarks and Introductions**
12:05 PM – 12:25 PM	**U.S. Department of Energy Summary**
12:25 PM – 1:40 PM	**Extraction of Raw Materials**
1:40 PM – 2:55 PM	**Refinement of Raw Materials – Conversion to Sulfates**
2:55 PM – 3:00 PM	**Wrap up and Closing Comments**

December 17, 2020

AGENDA

Please note that meeting times for topics each day are approximate and may be adjusted based on discussion during the meeting.

DAY 3: December 17th – Cathode Manufacturing

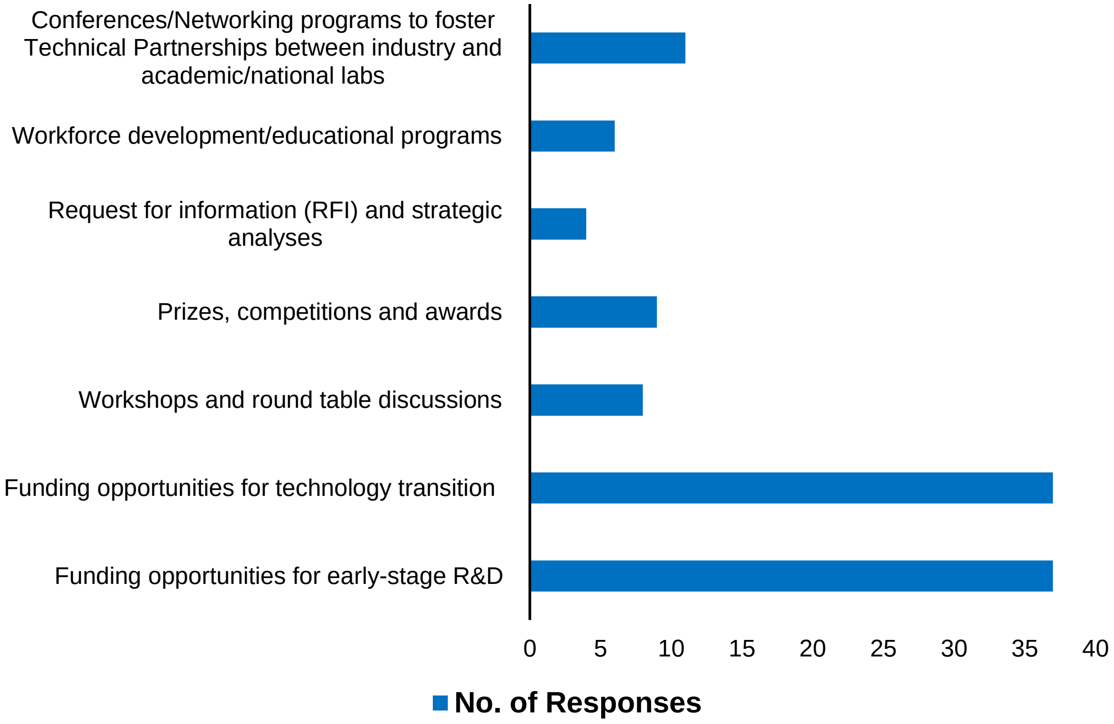
12:00 PM – 3:00 PM EST

Time	Activity
12:00 PM – 12:05 PM	**Welcoming Remarks and Introductions**
12:05 PM – 12:25 PM	**U.S. Department of Energy Summary**
12:25 PM – 1:15 PM	**Current and Future Trends**
1:15 PM – 2:05 PM	**Gaps and Barriers**
2:05 PM – 2:55 PM	**Technology Development**
2:55 PM – 3:00 PM	**Wrap up and Closing Comments**

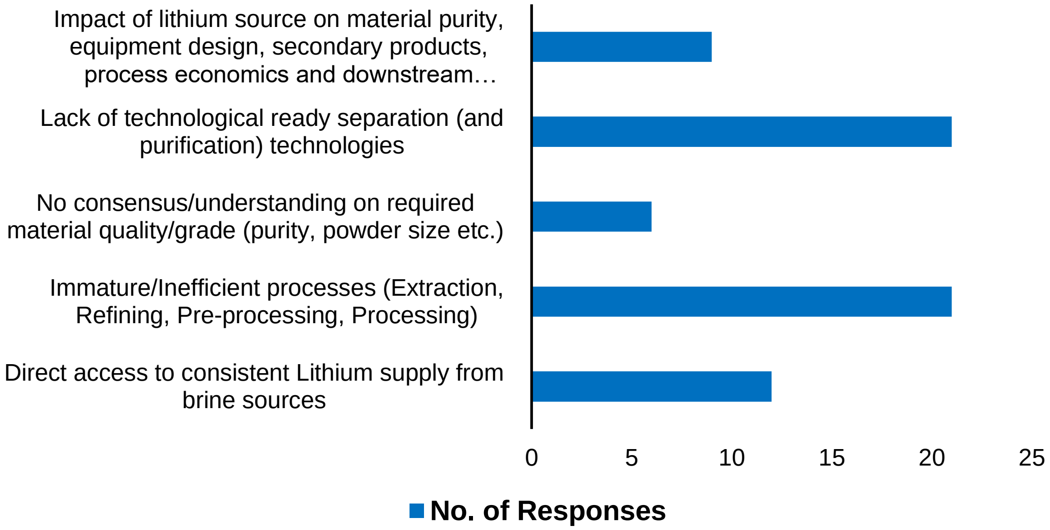
APPENDIX B: Poll Results

Day 1

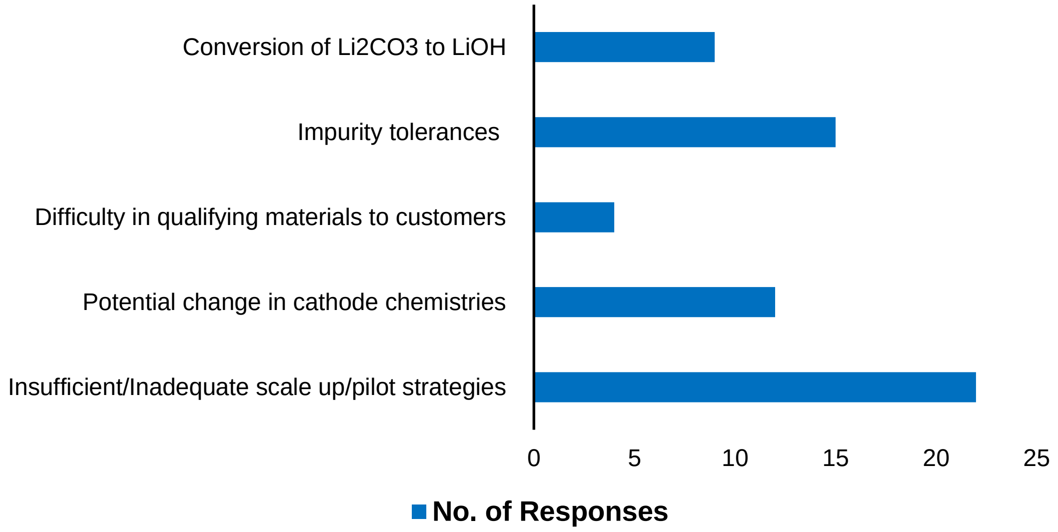
Q1. What is the best use of government investment or federal programs that will strengthen U.S. manufacturing and recyclability and reduce dependence on foreign sources of critical materials?



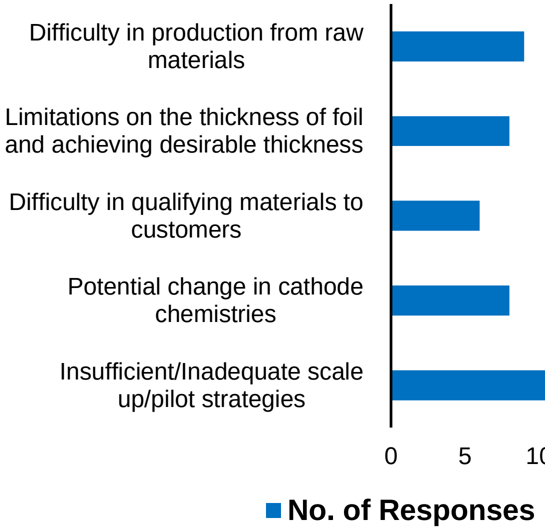
Q2. What is the main bottle neck that you experience regarding lithium processing/manufacturing from brines/hardrock?



Q3. What are the key factors that will make LiOH economic and what barriers remain to achieve cost-competitiveness?

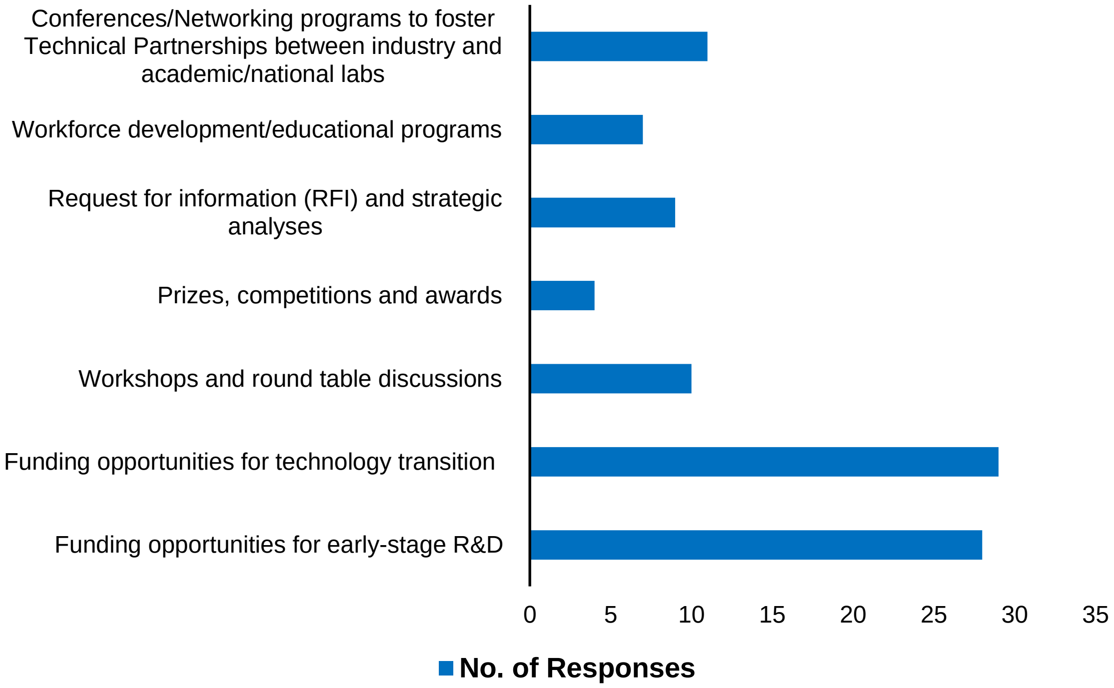


Q4. What are the key factors that will make Li foil/metal for next-generation technologies economic and what barriers remain to achieve cost-competitiveness?

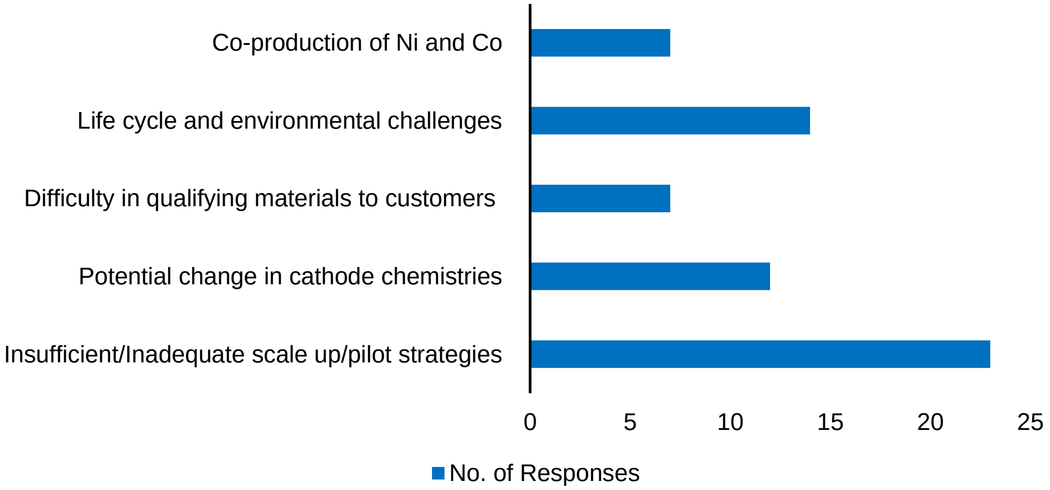


Day 2

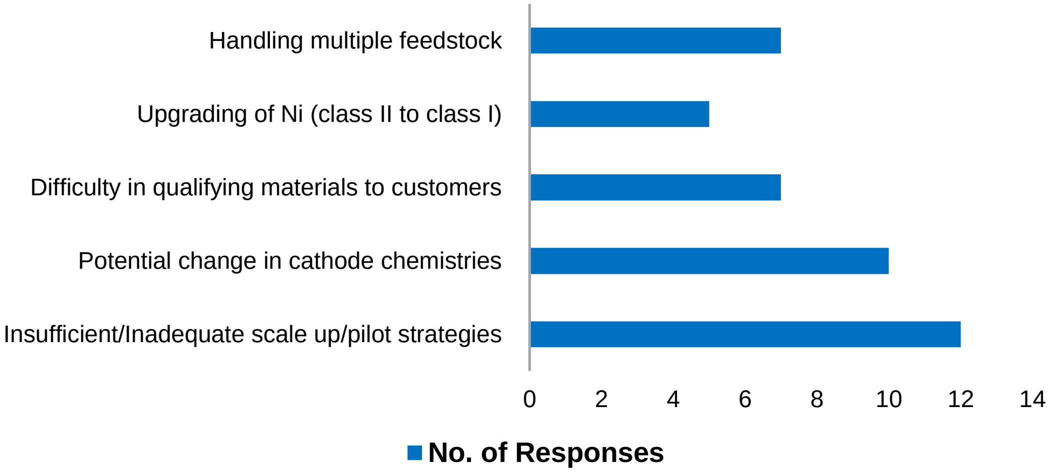
Q1. What is the best use of government investment or federal programs that will strengthen U.S. manufacturing and recyclability and reduce dependence on foreign sources of critical materials?



Q2. What are the greatest scientific/technical/engineering challenges to bringing domestic Ni and Co mining online?

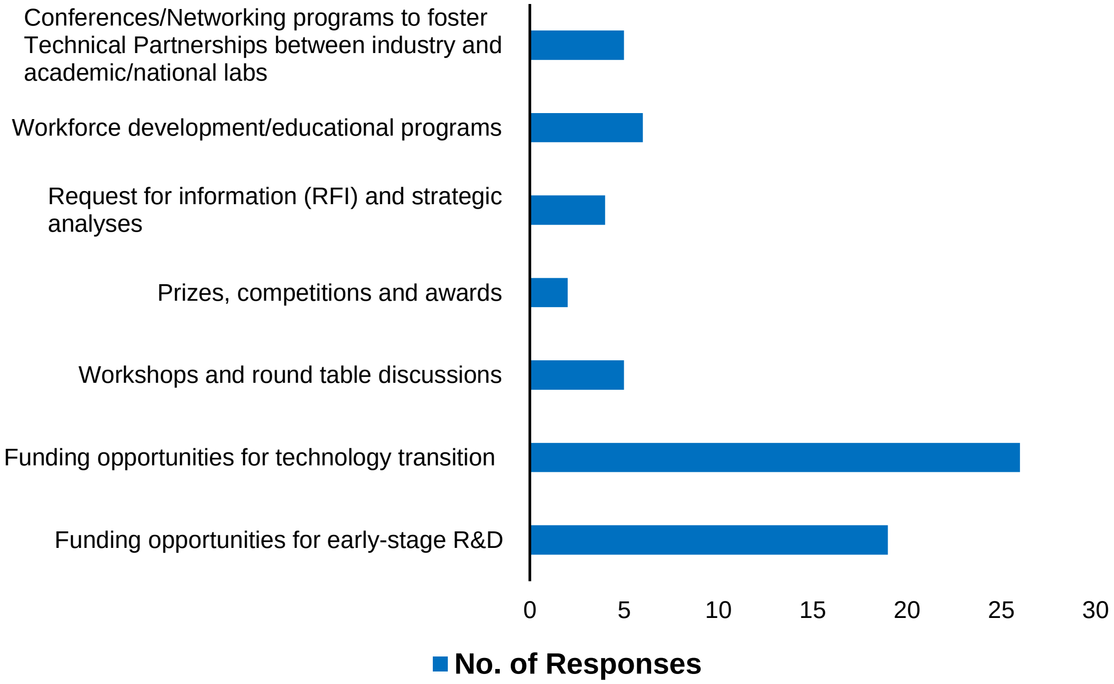


Q3. What is the largest cost driver for battery grade precursor production?

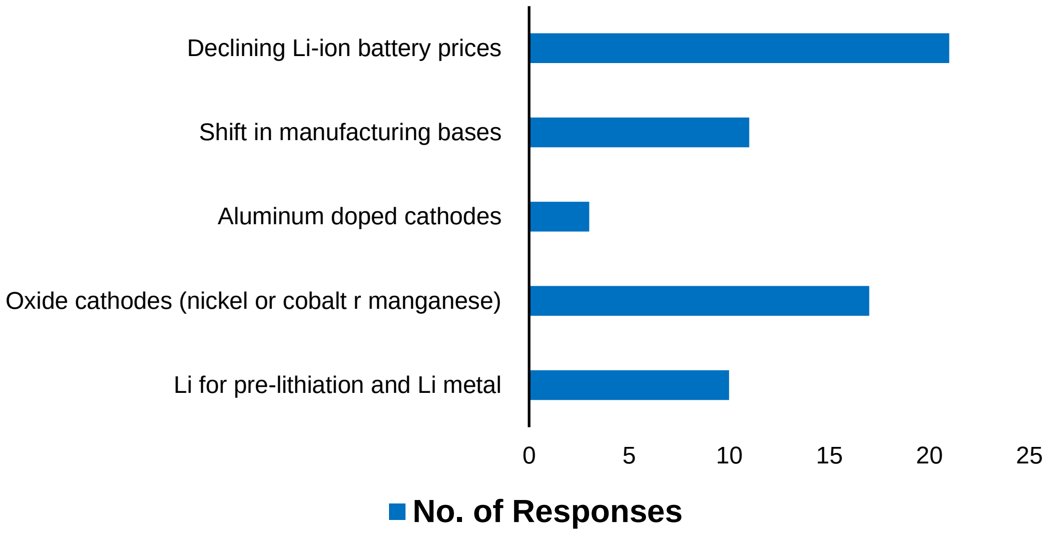


Day 3

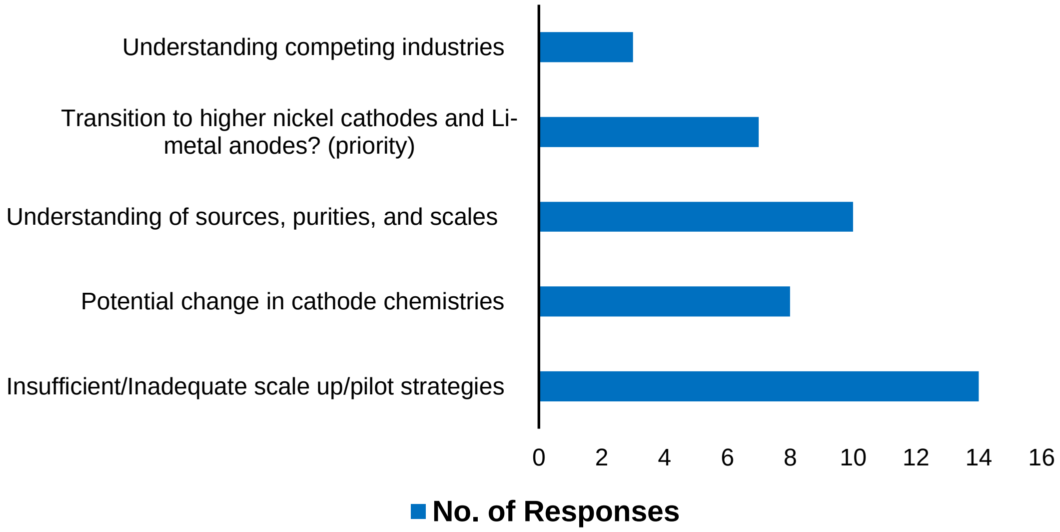
Q1. What is the best use of government investment or federal programs that will strengthen U.S. manufacturing and recyclability and reduce dependence on foreign sources of critical materials?



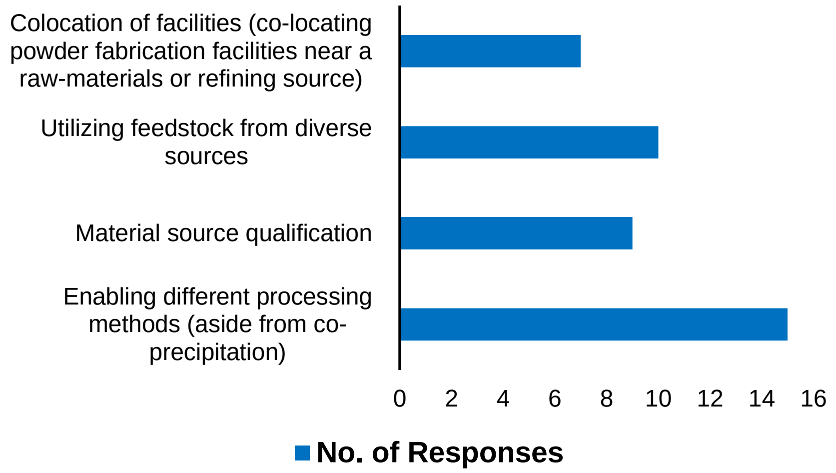
Q2. What key trends related to battery materials will be relevant in the next 5-10 years?



Q3. What are the major gaps and barriers associated with cathode manufacturing?



Q4. What key actions could enable technology development for cathode manufacturing?



APPENDIX C: List of Participants

Day 1

First Name	Last Name	Affiliation	Role
Ezinne	Achinivu*	U.S. Department of Energy	Observer
Jeffrey	Akomah	Natural Resources Canada	Observer
Barry	Basile	U.S. Department of Energy	Observer
Stephen	Belmont	Albemarle Corporation	Observer
Michael	Berube	U.S. Department of Energy	Active Participant
Eric	Besseling	BHE Minerals	Active Participant
Ramesh	Bhave	Oak Ridge National Laboratory	Active Participant
Jerel J.	Bogdan, PE	Eureka Resources	Observer
Ross	Brindle*	Nexight Group	Active Participant
Clinton	Britt	Congressman Paul D. Tonko	Observer
Joe	Bush	Battery Resourcers	Active Participant
Halle	Cheeseman	U.S. Department of Energy	Observer
Lei	Cheng	Argonne National Laboratory	Observer
Pengbo	Chu	University of Nevada, Reno	Observer
Mallory	Clites*	U.S. Department of Energy	Active Participant
Hoshi	Daruwalla	EcoPro BM	Active Participant
Patrick	Dobson	Lawrence Berkeley National Laboratory	Active Participant
Rod	Eggert	Colorado School of Mines	Observer
Aaron	Feaver	JCDREAM / WSU (Joint Center for Deployment and Research in Earth Abundant Materials)	Observer
Sara	Ferchichi	U.S. Department of State	Observer
Sarah	Forbes	U.S. Department of Energy	Observer
Yoshiko	Fujita	Idaho National Laboratory	Observer
Linda	Gaines	Argonne National Laboratory	Observer
Samm	Gillard*	U.S. Department of Energy	Active Participant
Daniel	Ginosar	Idaho National Laboratory	Active Participant
Fred	Gius	California Geological Survey	Observer
Gregory	Halder	Argonne National Laboratory	Observer

Amanda	Hall	Summit Nanotech Corporation	Active Participant
Carol	Handwerker	Purdue University	Active Participant
Stephen	Harrison	Rakehill Technologies LLC	Active Participant
Jonathan	Harter	Oak Ridge National Laboratory	Observer
Stephen	Hendrickson	U.S. Department of Energy	Observer
Gregory	Horrocks	Air Force Research Laboratory	Observer
Annie	Huhta	University of Nevada, Reno	Observer
Chukwunwike	Iloeje	Argonne National Laboratory	Observer
Hongyue	Jin	University of Arizona	Observer
Erica	Key	California Geological Survey	Observer
Helena	Khazdozian*	U.S. Department of Energy	Observer
John	Klaehn	Idaho National Laboratory	Observer
Thomas	Kodenkandath	Hazen Research	Active Participant
Rachel	Lanspa*	Nexight Group	Active Participant
Tedd	Lister	Idaho National Laboratory	Active Participant
Barbara	Little	Albemarle Corporation	Observer
Thomas	Lograsso	Critical Materials Institute, Ames Laboratory	Active Participant
Kevin	Lyon	Idaho National Laboratory	Active Participant
Alex	Macdonald	Rio Tinto Borates and Lithium	Observer
Rahul	Malik	CAMX Power	Observer
Margaret	Mann	National Renewable Energy Laboratory	Active Participant
Manikandadas	Mathilakathu Madathil	U. S. Borax	Active Participant
Helaina	Matza	U.S. Department of State	Observer
Alexis	McKittrick	U.S. Department of Energy	Observer
Mike	McKittrick	U.S. Department of Energy	Observer
Katherine	McMahon	U.S. Geological Survey	Observer
Jeremy	Mehta	U.S. Department of Energy	Observer
Bruce	Moyer	Critical Materials Institute	Observer
Jennifer	Nelson	CAMX Power	Observer
Michael	O'Connor*	U.S. Department of Energy	Observer

Richard	Oldland	Albemarle	Observer
Lindsay	Pack*	Nexight Group	Active Participant
Lei	Pan	Michigan Tech	Active Participant
Parans	Paranthaman	Oak Ridge National Laboratory	Active Participant
Maria	Pereyra-Vera	U.S. Department of Energy	Observer
Catalina	Polanco	Albemarle	Observer
Robert	Privette	Umicore Rechargeable Battery Materials	Active Participant
Denis	Prodius	Ames Laboratory/Critical Materials Institute	Observer
Vicky	Putsche	National Renewable Energy Laboratory	Observer
David	Reed	Idaho National Laboratory	Observer
Andy	Robinson	Standard Lithium	Active Participant
Sandip	Shinde	Rio Tinto Borates and Lithium	Active Participant
Morgan	Smith*	Nexight Group	Active Participant
Jeff	Spangenberger	Argonne National Laboratory	Active Participant
Venkat	Srinivasan	Argonne National Laboratory	Active Participant
Suresh	Sriramulu	CAMX Power LLC	Observer
Caleb	Stetson	Idaho National Laboratory	Observer
Mark	Strauss	Idaho National Laboratory	Observer
William	Stringfellow	Berkeley National Laboratory	Observer
Daniel	Suasnabar	Rio Tinto	Observer
Sarang	Supekar	Argonne National Laboratory	Active Participant
Alexander	Thompson	Albemarle Corporation	Observer
Mai	Tran	U.S. Department of Energy	Observer
Ehsan	Vahidi	University of Nevada, Reno	Observer
Priyesh	Wagh	Oak Ridge National Laboratory	Observer
Yan	Wang	Worcester Polytechnic Institute	Active Participant
Charlene	Wardlow	CA Geologic Energy Management Division	Observer
Ian	Warren	National Renewable Energy Laboratory	Active Participant
Dustin	Weigl	National Renewable Energy Laboratory	Observer
Jonathan	Weisgall	Berkshire Hathaway Energy Co.	Active Participant

Jeff	Winick	Boston Government Services	Observer
Ben	Yu	National Research Council Canada	Observer
Janice	Zinck	Natural Resources Canada	Observer

** planning team and facilitators*

Day 2

First Name	Last Name	Affiliation	Role
Ezinne	Achinivu*	U.S. Department of Energy	Observer
Abdessadek	Ait si brahim	Glencore	Observer
Jeffrey	Akomah	Natural Resources Canada	Observer
Majid	Alipanah Doolabi	University of Arizona	Observer
Barry	Basile	U.S. Department of Energy	Observer
Jacob	Beaver	Prime Policy Group	Observer
Ramesh	Bhave	Oak Ridge National Laboratory	Active Participant
Mike	Blakeney	Cobalt Institute	Active Participant
Ross	Brindle*	Nexight Group	Active Participant
Halle	Cheeseman	U.S. Department of Energy	Observer
Lei	Cheng	Argonne National Laboratory	Observer
Pengbo	Chu	University of Nevada, Reno	Observer
Mallory	Clites*	U.S. Department of Energy	Active Participant
Hoshi	Daruwalla	EcoPro BM	Active Participant
Rod	Eggert	Colorado School of Mines	Observer
Aaron	Feaver	JCDREAM / WSU (Joint Center for Deployment and Research in Earth Abundant Materials)	Observer
Sara	Ferchichi	U.S. Department of State	Observer
Yoshiko	Fujita	Idaho National Laboratory	Observer
Linda	Gaines	Argonne National Laboratory	Observer
Samm	Gillard*	U.S. Department of Energy	Active Participant
Daniel	Ginosar	Idaho National Laboratory	Active Participant
Fred	Gius	California Geological Survey	Observer
Gregory	Halder	Argonne National Laboratory	Observer

Susan	Hamm	U.S. Department of Energy	Active Participant
Carol	Handwerker	Purdue University	Active Participant
Stephen	Hendrickson	U.S. Department of Energy	Observer
Subramanya	Herle	Applied Materials	Observer
Gregory	Horrocks	Air Force Research Laboratory	Observer
Chukwunwike	Iloeje	Argonne National Laboratory	Observer
Hongyue	Jin	University of Arizona	Observer
Jessica	Johnson	Talon Metals	Observer
Jarod	Kelly	Argonne National Laboratory	Observer
Erica	Key	California Geological Survey	Observer
Helena	Khazdozian*	U.S. Department of Energy	Observer
Jai-woh	Kim	U.S. Department of Energy	Observer
John	Klaehn	Idaho National Laboratory	Observer
Thomas	Kodenkandath	Hazen Research	Active Participant
Tedd	Lister	Idaho National Laboratory	Active Participant
Thomas	Lograsso	Critical Materials Institute, Ames Laboratory	Active Participant
Rahul	Malik	CAMX Power	Observer
Margaret	Mann	National Renewable Energy Laboratory	Active Participant
Katherine	McMahon	U.S. Geological Survey	Observer
Michele	McRae	USGS	Observer
Jeremy	Mehta	U.S. Department of Energy	Observer
Ted	Miller	Ford Motor Company	Observer
Michael	Moats	Missouri University of Science and Technology	Observer
Ikenna	Nlebedim	Ames Laboratory	Observer
Lei	Pan	Michigan Tech	Active Participant
Oliver	Peters	Talon Metals	Active Participant
Robert	Privette	Umicore Rechargeable Battery Materials	Active Participant
Vicky	Putsche	National Renewable Energy Laboratory	Observer
David	Reed	Idaho National Laboratory	Observer
Jayson	Ripke	The Doe Run Company	Observer

Sandip	Shinde	Rio Tinto Borates and Lithium	Active Participant
Morgan	Smith	Nexight Group	Active Participant
Jeff	Spangenberger	Argonne National Laboratory	Active Participant
Suresh	Sriramulu	CAMX Power LLC	Observer
Caleb	Stetson	Idaho National Laboratory	Observer
William	Stringfellow	Berkeley National Laboratory	Observer
Daniel	Suasnabar	Rio Tinto	Observer
Sarang	Supekar	Argonne National Laboratory	Active Participant
Bennson	Tanda	The Doe Run Company	Active Participant
Patrick	Taylor	Colorado School of Mines	Active Participant
Mai	Tran	U.S. Department of Energy	Observer
Ehsan	Vahidi	University of Nevada, Reno	Observer
Henri	van Rooyen	Talon Metals	Active Participant
Priyesh	Wagh	Oak Ridge National Laboratory	Observer
Ian	Warren	National Renewable Energy Laboratory	Active Participant
Dustin	Weigl	National Renewable Energy Lab	Observer
Ben	Yu	National Research Council Canada	Observer

** planning team and facilitators*

Day 3

First Name:	Last Name:	Affiliation	Role
Ezinne	Achinivu*	U.S. Department of Energy	Observer
Jeffrey	Akomah	Natural Resources Canada	Observer
Majid	Alipanah Doolabi	University of Arizona	Observer
Mike	Blakeney	Cobalt Institute	Active Participant
Ross	Brindle*	Nexight Group	Active Participant
Joe	Bush	Battery Resourcers	Active Participant
Thomas	Carney	CAMX Power	Observer
Halle	Cheeseman	U.S. Department of Energy	Observer
Lei	Cheng	Argonne National Laboratory	Observer
Mallory	Clites*	U.S. Department of Energy	Active Participant
Hoshi	Daruwalla	EcoPro BM	Active Participant
Aaron	Feaver	JCDREAM / WSU (Joint Center for Deployment and Research in Earth Abundant Materials)	Observer
Sara	Ferchichi	U.S. Department of State	Observer
Sarah	Forbes	U.S. Department of Energy	Observer
Samm	Gillard*	U.S. Department of Energy	Active Participant
Eric	Gratz	Battery Resourcers Inc	Active Participant
Susan	Hamm	U.S. Department of Energy	Active Participant
Carol	Handwerker	Purdue University	Active Participant
Stephen	Hendrickson	U.S. Department of Energy	Observer
Gregory	Horrocks	Air Force Research Laboratory	Observer
Chukwunwike	Iloeje	Argonne National Laboratory	Observer
Hongyue	Jin	University of Arizona	Observer
Jarod	Kelly	Argonne National Laboratory	Observer
Helena	Khazdozian*	U.S. Department of Energy	Observer
John	Klaehn	Idaho National Laboratory	Observer
Thomas	Kodenkandath	Hazen Research	Active Participant
Thomas	Lograsso	Critical Materials Institute, Ames Laboratory	Active Participant

Kevin	Lyon	Idaho National Laboratory	Active Participant
Rahul	Malik	CAMX Power	Observer
Margaret	Mann	National Renewable Energy Laboratory	Active Participant
Michele	McRae	USGS	Observer
Jeremy	Mehta	U.S. Department of Energy	Observer
Michael	Moats	Missouri University of Science and Technology	Observer
Jennifer	Nelson	CAMX Power	Observer
Ikenna	Nlebedim	Ames Laboratory	Observer
Lei	Pan	Michigan Tech	Active Participant
Parans	Paranthaman	Oak Ridge National Laboratory	Active Participant
Robert	Privette	Umicore Rechargeable Battery Materials	Active Participant
Vicky	Putsche	National Renewable Energy Laboratory	Observer
Job	Rijssenbeek	Albemarle Corporation	Active Participant
Sandip	Shinde	Rio Tinto Borates and Lithium	Active Participant
Morgan	Smith*	Nexight Group	Active Participant
Jeff	Spangenberger	Argonne National Laboratory	Active Participant
Venkat	Srinivasan	Argonne National Laboratory	Active Participant
Suresh	Sriramulu	CAMX Power LLC	Observer
Daniel	Suasnabar	Rio Tinto	Observer
Sarang	Supekar	Argonne National Laboratory	Active Participant
Mai	Tran	U.S. Department of Energy	Observer
Ehsan	Vahidi	University of Nevada, Reno	Observer
Henri	van Rooyen	Talon Metals	Active Participant
Robbie	Villemarette	Albemarle Corporation	Observer
Yan	Wang	Worcester Polytechnic Institute	Active Participant
Dustin	Weigl	National Renewable Energy Lab	Observer
Casey	Westhoff	Umicore USA Inc	Observer
Michael	Wixom	Navitas Systems	Observer
Ben	Yu	National Research Council Canada	Observer

** planning team and facilitators*

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