FINDINGS REPORT:

VIRTUAL WORKSHOP ON 'RESILIENT SUPPLY OF CRITICAL MINERALS'

02-03 August, 2021. Hosted by Missouri S&T.

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O'KEEFE INSTITUTE SUSTAINABLE SUPPLY OF STRATEGIC MINERALS

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Acknowledgements and Disclaimer

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The workshop was initially planned for May 2020 on the Missouri S&T campus, Rolla, Missouri, USA. Owing to the global COVID-19 pandemic, the format of the workshop was changed to a hybrid virtual / in-person mode. The virtual workshop on August 2-3, 2021, which findings are presented here, will be followed by an in-person workshop in mid-2022 (subject to change if the COVID-19 pandemic remains a health concern).

The findings presented in this report are solely based on discussions during the workshop, i.e., keynote lectures and breakout sessions. The views and opinions presented here do not necessarily reflect those of the workshop organizers who prepared the report.

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Executive Summary

On August 2-3, 2021, the Thomas J. O'Keefe Institute for Sustainable Supply of Strategic Minerals at Missouri University of Science and Technology (Missouri S&T) hosted the NSF-funded virtual workshop 'Resilient Supply of Critical Minerals'. The workshop was convened via Zoom and attracted 158 registrants, including 108 registrants from academia (61 students), 30 registrants from government agencies, and 20 registrants from the private sector. Four topical sessions were covered:

A. Mineral Exploration and Source Diversification.
B. Supply Chain and Policy Issues.
C. Improving Mineral Recycling and Reprocessing Technologies.
D. Technological Alternatives to Critical Minerals.

Each topical session was composed of two keynote lectures and followed by a breakout session that was designed to identify promising pathways towards increasing critical supply chain resilience in the United States. During each breakout session, participants were asked to address five questions:

Q1. What are the roadblocks that affect the resilient supply of critical minerals?

Q2. What are the most pressing research needs?

Q3. What opportunities can lead to the fastest and biggest impact?

Q4. What skills training is required to meet future workforce demands?

Q5. What other questions should be asked, but are commonly overlooked?

Several issues that limit critical mineral supply chain resilience in the United States were identified and discussed in all breakout sessions, including:

1. <u>Insufficient understanding of domestic critical minerals resources</u>. To address this issue, workshop participants highlighted the need for (i) more geologic research to identify new and evaluate existing resources; and (ii) a qualitative and quantitative assessment of critical minerals that may be recovered as by/co-products from existing production streams.
2. <u>Technical limitations of current mineral processing and recycling technologies.</u> To address this issue, workshop participants highlighted the need for (i) innovative mineral processing technologies, including more environmentally friendly chemicals/solvents, and (ii) automated recycling technologies for appliances and e-waste. Participants also highlighted the need for a centralized and simplified way to collect recyclable materials, and incentives for the public to participate in recycling.
3. <u>Long permitting processes for mining and mineral processing operations, with often unpredictable outcomes</u>. To address this issue, workshop participants

suggested the development of new critical mineral focused policies with faster processing times and more transparent / predictable decision-making processes.

4. The negative public image of mining and mineral processing operations. To address this issue, workshop participants suggested to design public outreach / education initiatives and to include local communities into decision-making processes.
5. Limited availability of a critical mineral workforce. To address this issue, workshop participants suggested an increased focus on critical mineral specific skill training in higher education institutions, and advanced training of the existing workforce.

1. Introduction

On June 4, 2019, the U.S. Department of Commerce released the strategic report "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals". This report outlines six Calls to Action that, if executed, will reduce the vulnerability of the United States to critical mineral supply disruptions. These six Calls to Action are:

1. Advance Transformational Research, Development, and Deployment Across Critical Mineral Supply Chains.
2. Strengthen America's Critical Mineral Supply Chains and Defense Industrial Base.
3. Enhance International Trade and Cooperation Related to Critical Minerals.
4. Improve Understanding of Domestic Critical Mineral Resources.
5. Improve Access to Domestic Critical Mineral Resources on Federal Lands and Reduce Federal Permitting Timeframes.
6. Grow the American Critical Minerals Workforce.

In 2020, the Thomas J. O'Keefe Institute for Sustainable Supply of Strategic Minerals at Missouri University of Science and Technology (Missouri S&T) received funding from the National Science Foundation (NSF) to host a workshop on the Missouri S&T campus (Rolla, Missouri) to identify research needs associated with these Calls to Action. Initially scheduled for May 2020, the in-person workshop was cancelled because of the global COVID-19 pandemic. The format of the workshop was changed to a two-part hybrid mode, comprising (i) a virtual workshop held via Zoom on August 2-3, 2021; and (ii) an in-person workshop currently expected to be held in mid-2022. The virtual 2-day workshop was divided into 4 themed topical sessions:

Day 1:

Session A: Mineral Exploration and Source Diversification.

Keynote Lectures:

- **Thomas C. Crafford, Warren C. Day, Michael J. Magyar** (National Minerals Information Center, U.S. Geological Survey): *The critical mineral potential of the United States and USGS efforts to facilitate new mineral resource discovery.*
- **John Uhrie** (Doe Run Company): *Critical mineral resources and the challenges to providing them into America's supply chain.*

Session B: Supply Chain and Policy Issues.

Keynote Lectures:

- **Thomas E. Graedel** (School of Forestry & Environmental Studies, Yale University): *The implications of technological innovations for critical mineral supply chains.*
- **Julie M. Klinger**, Department of Geography and Spatial Sciences (University of Delaware): *Global rare earth politics: A pathway forward.*

Day 2:

Session C: Improving Mineral Recycling and Reprocessing Technologies.

Keynote Lectures:

- **Nedal T. Nassar** (National Minerals Information, Center, U.S. Geological Survey): *USGS' material flow modeling that it uses for criticality assessment and the role of recycling and reprocessing in determining criticality.*
- **Michael Moats** (O'Keefe Institute for Sustainable Supply of Strategic Minerals, Missouri University of Science and Technology): *Where have all the smelters gone? America's dependency on foreign non-ferrous metal production.*

Session D: Technological Alternatives to Critical Minerals.

Keynote Lectures:

- **Jon J. Kellar, Prasoon Diwakar, Samuel Kessinger** (Department of Materials and Metallurgical Engineering, South Dakota School of Mines and Technology): *The Illicit Economy and the Role of Critical Minerals.*
- **Roderick G. Eggert** (Critical Materials Institute, Colorado School of Mines): *Mineral resources for the energy transition: research needs for assuring resilient supply chains.*

The keynote lectures were followed by breakout sessions that discussed research needs associated with the four topical themes. During each breakout session, the workshop participants were asked to answer the same five questions:

- Q1. What are the roadblocks that affect the resilient supply of critical minerals?
- Q2. What are the most pressing research needs?
- Q3. What opportunities can lead to the fastest and biggest impact?
- Q4. What skills training is required to meet future workforce demands?
- Q5. What other questions should be asked, but are commonly overlooked?

This report summarizes the findings of the workshop's four breakout sessions.

2. Methods

Each breakout session independently discussed how critical mineral supply chain resilience can be improved in the United States within the framework of the topical themes. Two parallel breakout sessions were convened each day that followed the topical sessions of the day. Participants were asked during the workshop registration process which session they planned to attend (Fig. 1).

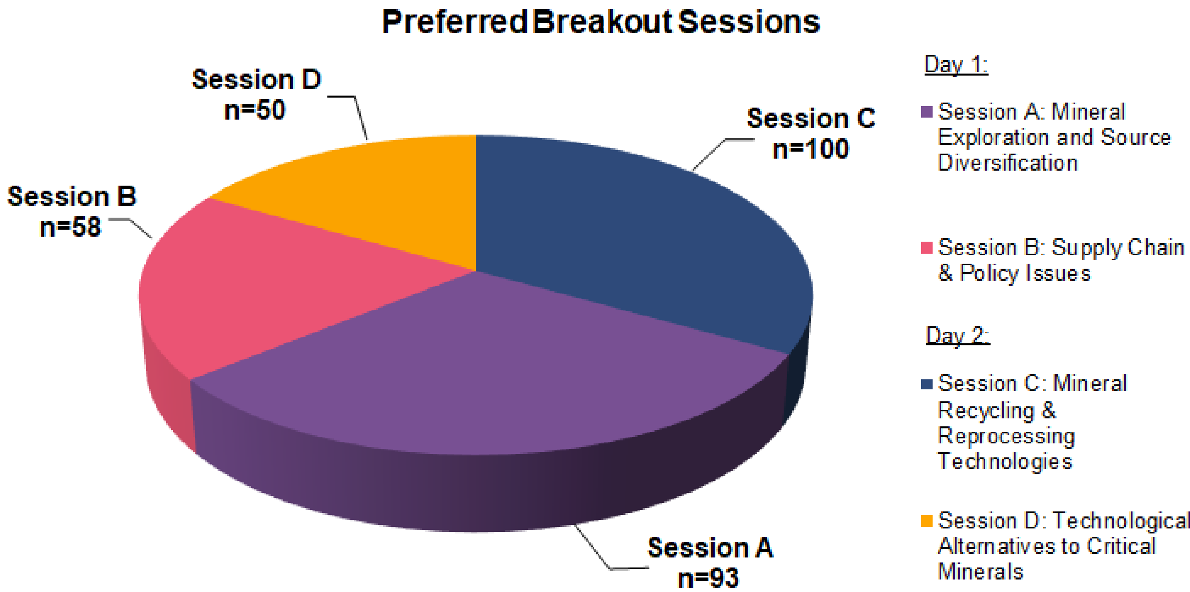

Figure 1: Preferred breakout sessions of workshop participants (n) as indicated during the workshop registration. Note that not all participants stated a preferred session for both days and were assigned a session randomly.

During the breakout sessions, the participants used Google Jamboard to address the five questions outlined above. Answers were added to Google Jamboard anonymously using Google Jamboard's *Post-It* function. The answers were grouped into categories to allow for the graphical and tabular presentations in Section 4: Breakout Sessions Results Summary.

3. Workshop Demographics

A total of 158 participants registered for the workshop, including 108 participants from academia, 30 from government agencies at the federal and state levels, and 20 from the private sector (Fig. 2-A). Participants from academia included 97 faculty/staff and 61 students (Fig. 2-B). Fourteen countries were represented in the workshop (Fig 3). The majority of participants were from the United States (n=143). Other represented countries included China (n=2), Peru (n=2), and one registered participant from each of the following countries: Austria, England, France, Ghana, India, Iran, Italy, Scotland, Sweden, Switzerland.

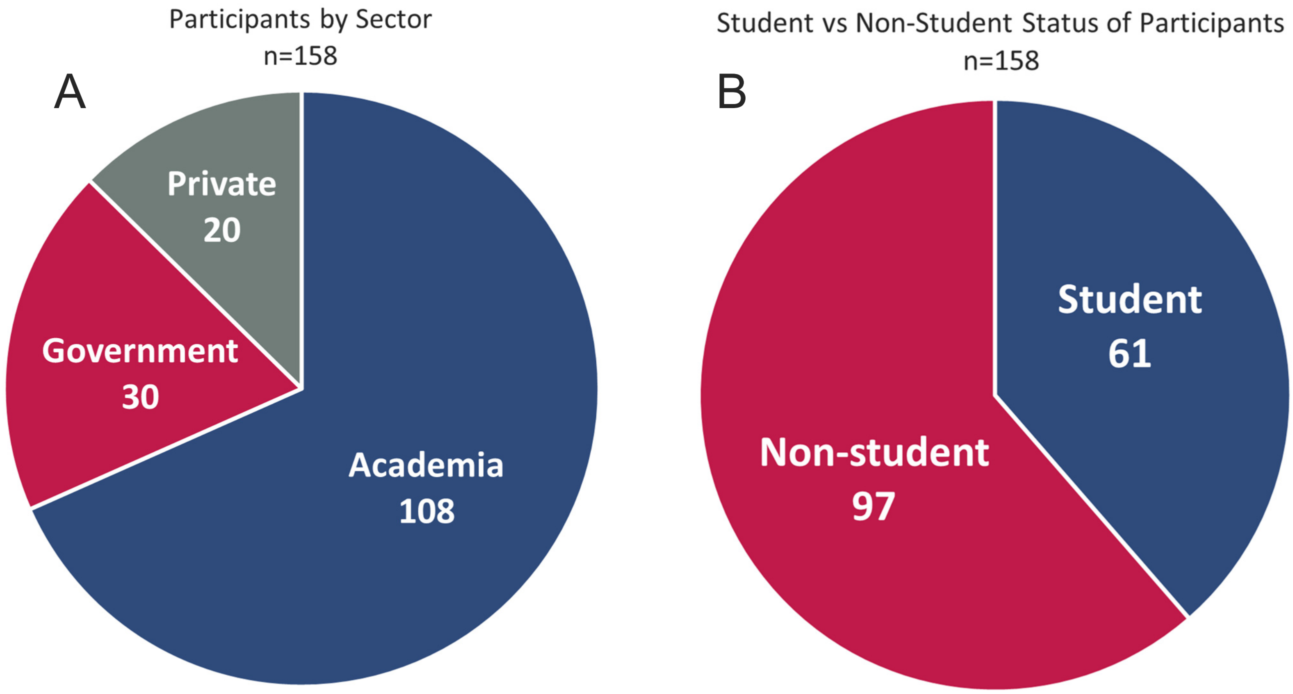

Figure 2: A) Breakdown of workshop participants based on sector of employment. B) Breakdown of student vs. non-student status of workshop registrants from academia.

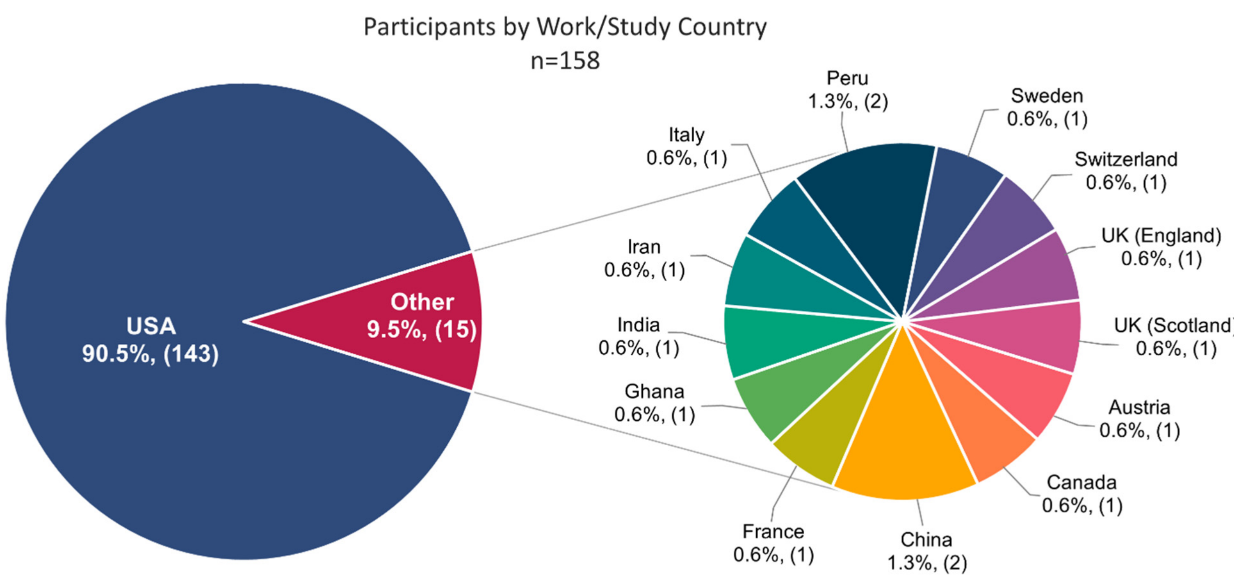

Figure 3: Workshop participants by country of residence.

4. Breakout Sessions Results Summary

The goal of the breakout sessions was to identify promising pathways towards increased critical supply chain resilience in the United States. Figure 4 summarizes the top-ten themes that were discussed during each session. A more detailed breakdown of the major themes, and the relative frequency in which they were mentioned by the participants, is presented in sections 4.1 to 4.4.

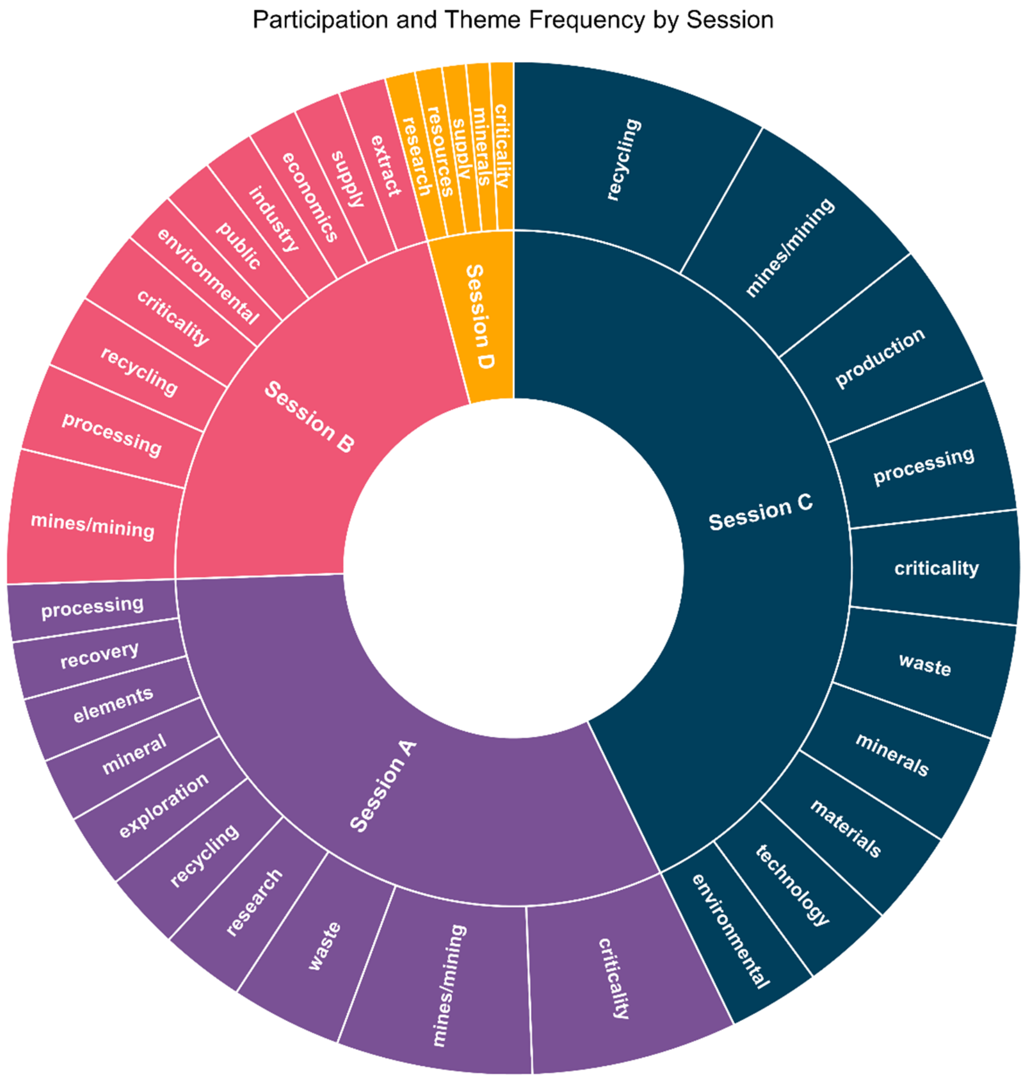

Figure 4: Overview of participation in the breakout sessions and top-10 themes mentioned during each breakout session. The size of individual pies reflects the relative frequency of which individual themes were mentioned.

4.1 Session A: Mineral Exploration and Source Diversification.

Figure 5 shows the top-40 themes mentioned during breakout session A and the frequency with which these themes were mentioned. Figures 6 and 7 present the data from Figure 6 visually in a word cloud and sunburst diagram, respectively. Representative answers to the five individual questions are presented and discussed in Chapter 5; a compilation of all answers is presented in Appendix B.

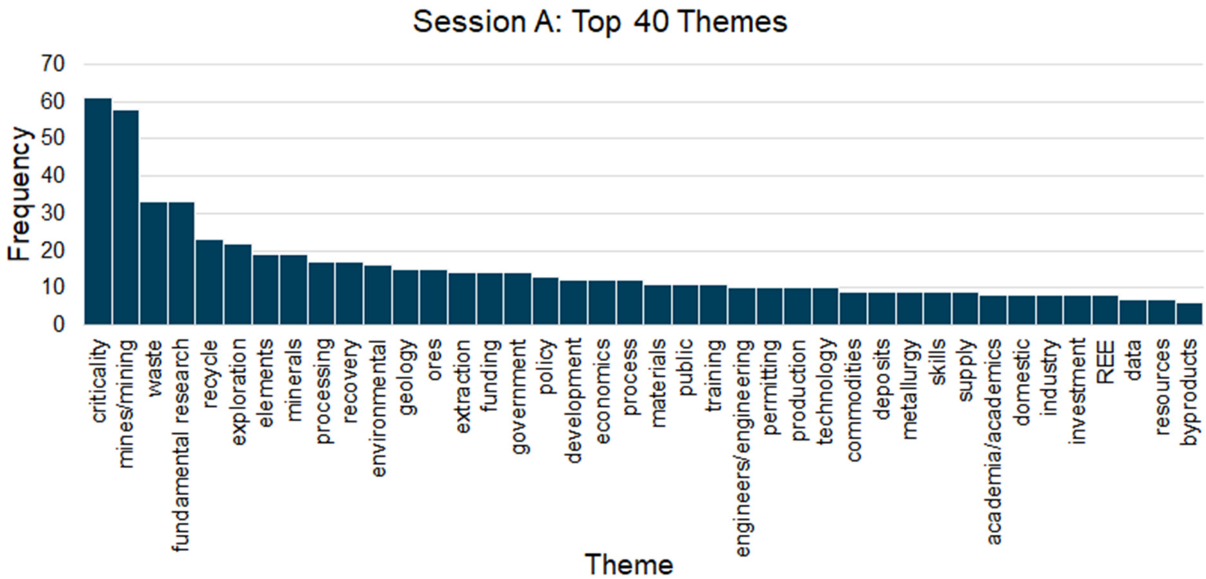

Figure 5: Top-40 themes mentioned during breakout session A: Mineral Exploration and Source Diversification. The themes cover all five questions asked during the breakout sessions.

Figure 6: Visualization of Figure 5 as a word cloud.

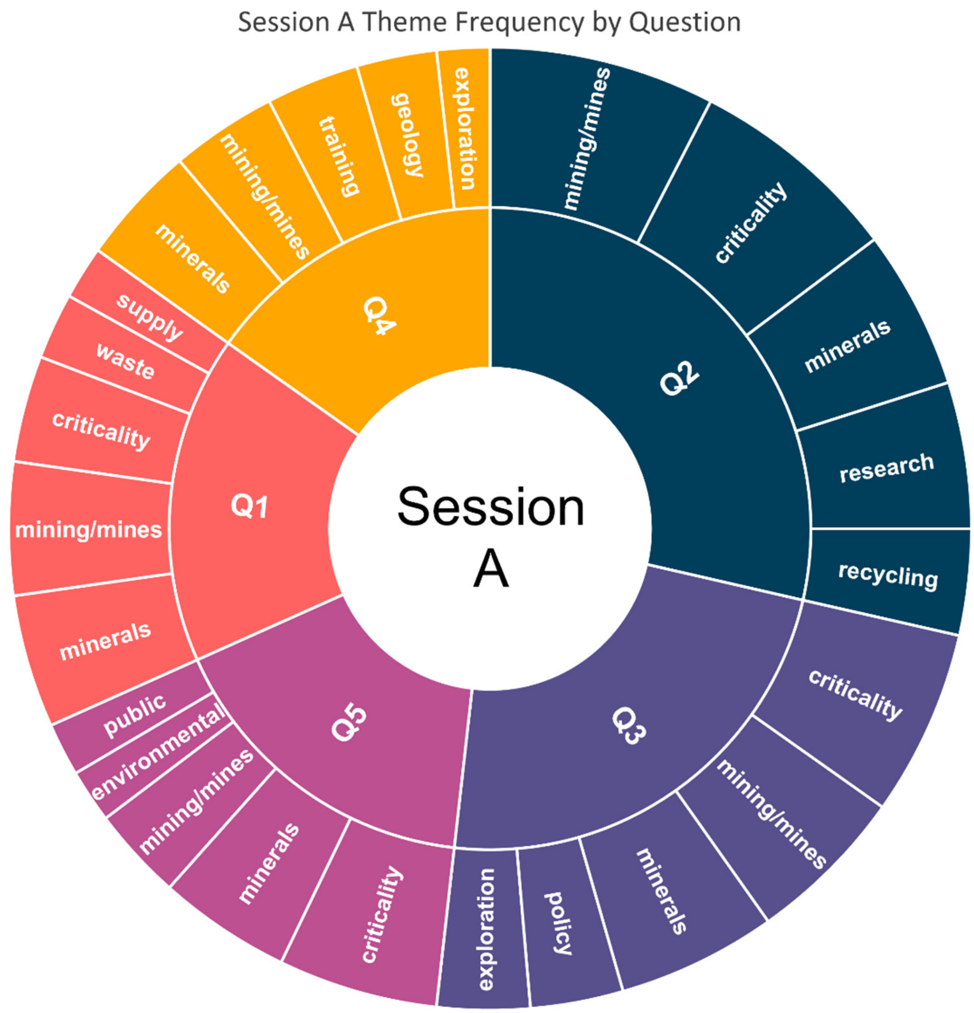

Figure 7: Top-5 themes mentioned in Session A: Mineral Exploration and Source Diversification in response to the five questions asked during each breakout session. The size of each pie slice indicates the relative frequency of mentions. Q1: What are the roadblocks that affect the resilient supply of critical minerals? Q2: What are the most pressing research needs? Q3: What opportunities can lead to the fastest and biggest impact? Q4: What skills training is required to meet future workforce demands? Q5: What other questions should be asked, but are commonly overlooked?

4.2 Session B: Supply Chain and Policy Issues

Figure 8 shows the top-40 themes mentioned during breakout session B and the frequency with which these themes were mentioned. Figures 9 and 10 present the data from Figure 8 visually in a word cloud and sunburst diagram, respectively. Representative answers to the five individual questions are presented and discussed in Chapter 5; a compilation of all answers is presented in Appendix B.

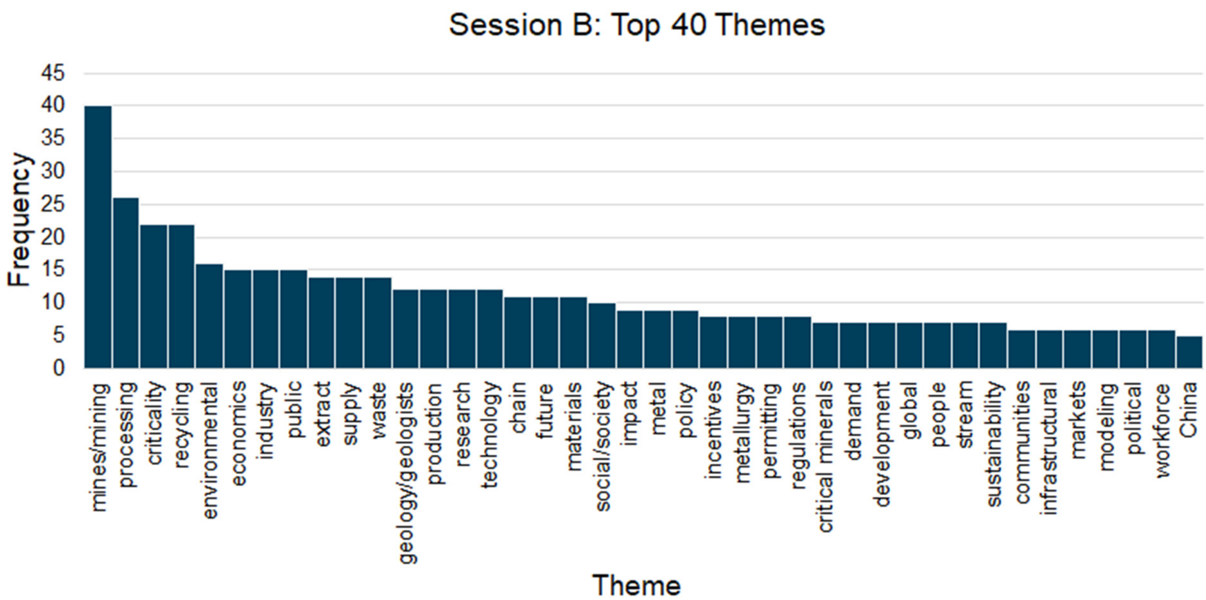

Figure 8: Top-40 themes mentioned during breakout session B: Supply Chain and Policy Issues. The themes cover all five questions asked during the breakout sessions.

Figure 9: Visualization of Figure 8 as a word cloud.

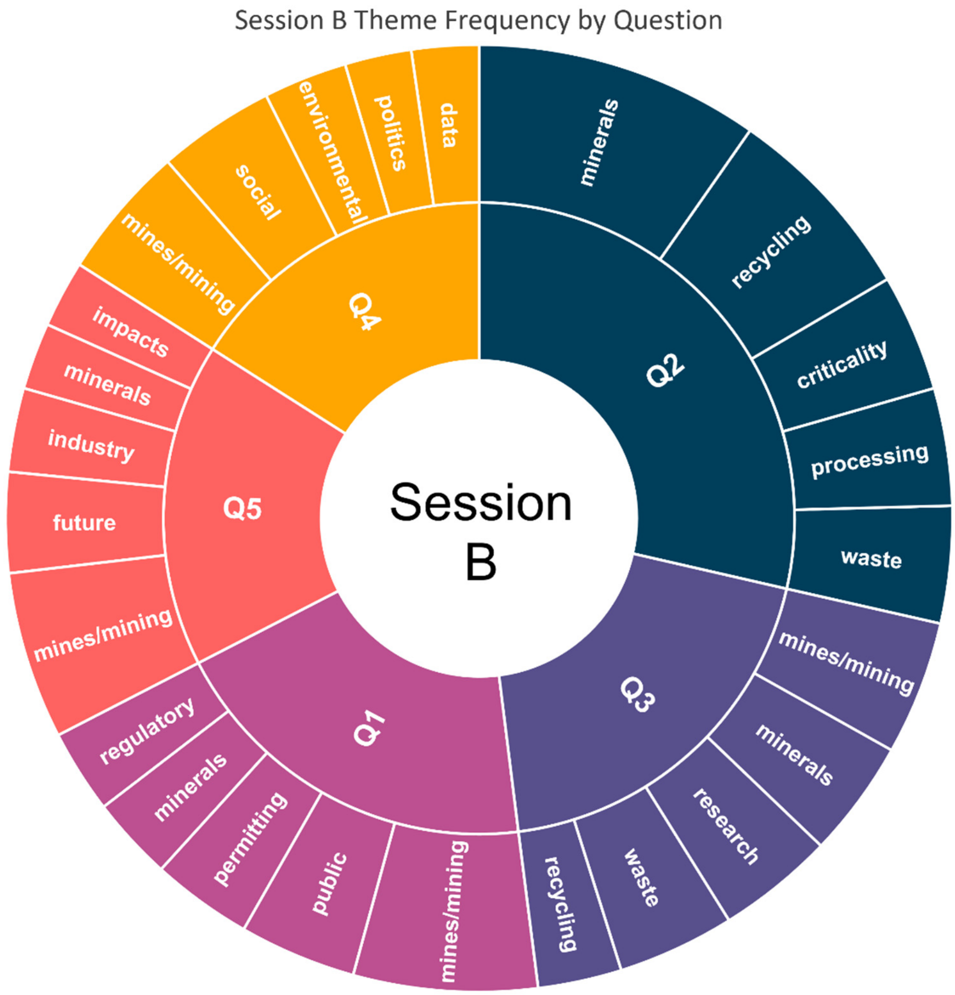

Figure 10: Top-5 themes mentioned in Session B: Supply Chain and Policy Issues in response to the five questions asked during each breakout session. The size of each pie slice indicates the relative frequency of mentions. Q1: What are the roadblocks that affect the resilient supply of critical minerals? Q2: What are the most pressing research needs? Q3: What opportunities can lead to the fastest and biggest impact? Q4: What skills training is required to meet future workforce demands? Q5: What other questions should be asked, but are commonly overlooked?

4.3 Session C: Improving Mineral Recycling and Reprocessing Technologies

Figure 11 shows the top-40 themes mentioned during breakout session C and the frequency with which these themes were mentioned. Figures 12 and 13 present the data from Figure 11 visually in a word cloud and sunburst diagram, respectively. Representative answers to the five individual questions are presented and discussed in Chapter 5; a compilation of all answers is presented in Appendix B.

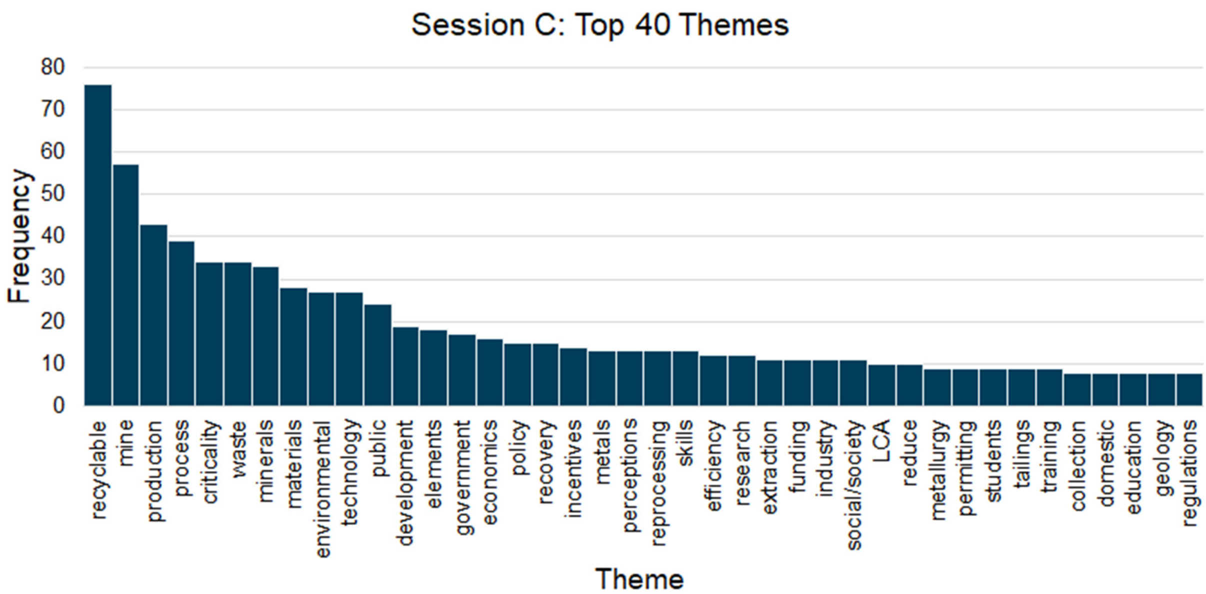

Figure 11: Top-40 themes mentioned during breakout session C: Improving Mineral Recycling and Reprocessing Technologies. The themes cover all five questions asked during the breakout sessions.

Figure 12: Visualization of Figure 11 as a word cloud.

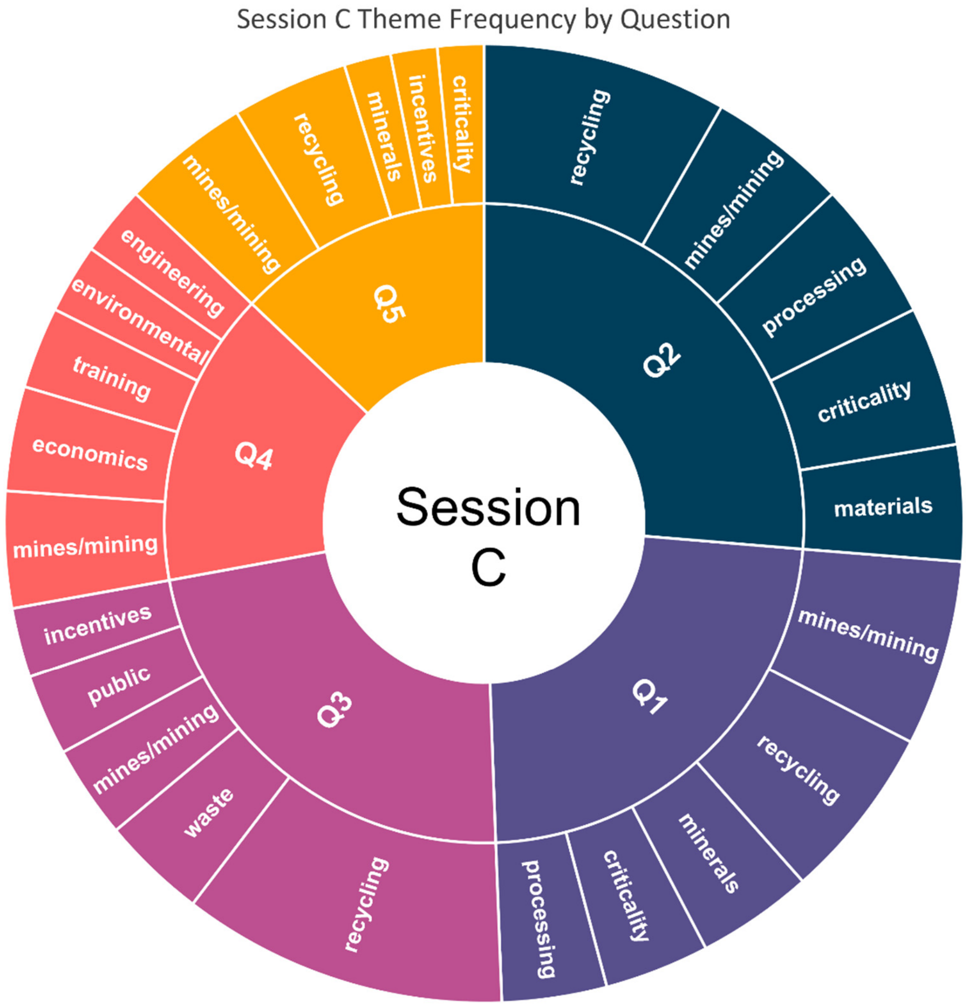

Figure 13: Top-5 themes mentioned in Session C: Improving Mineral Recycling and Reprocessing Technologies in response to the five questions asked during each breakout session. The size of each pie slice indicates the relative frequency of mentions. Q1: What are the roadblocks that affect the resilient supply of critical minerals? Q2: What are the most pressing research needs? Q3: What opportunities can lead to the fastest and biggest impact? Q4: What skills training is required to meet future workforce demands? Q5: What other questions should be asked, but are commonly overlooked?

4.4 Session D: Technological Alternatives to Critical Minerals

Figure 14 shows the top-40 themes mentioned during breakout session C and the frequency with which these themes were mentioned. Figures 15 and 16 present the data from Figure 14 visually in a word cloud and sunburst diagram, respectively. Representative answers to the five individual questions are presented and discussed in Chapter 5; a compilation of all answers is presented in Appendix B.

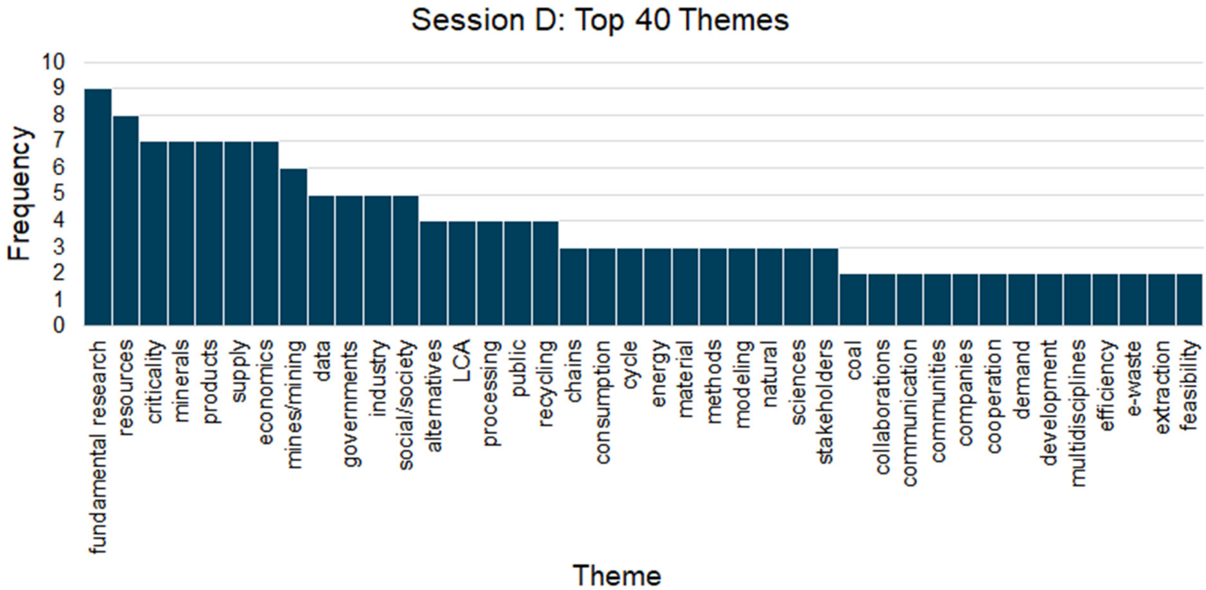

Figure 14: Top-40 themes mentioned during breakout session D: Technological Alternatives to Critical Minerals. The themes cover all five questions asked during the breakout sessions.

Figure 15: Visualization of Figure 14 as a word cloud.

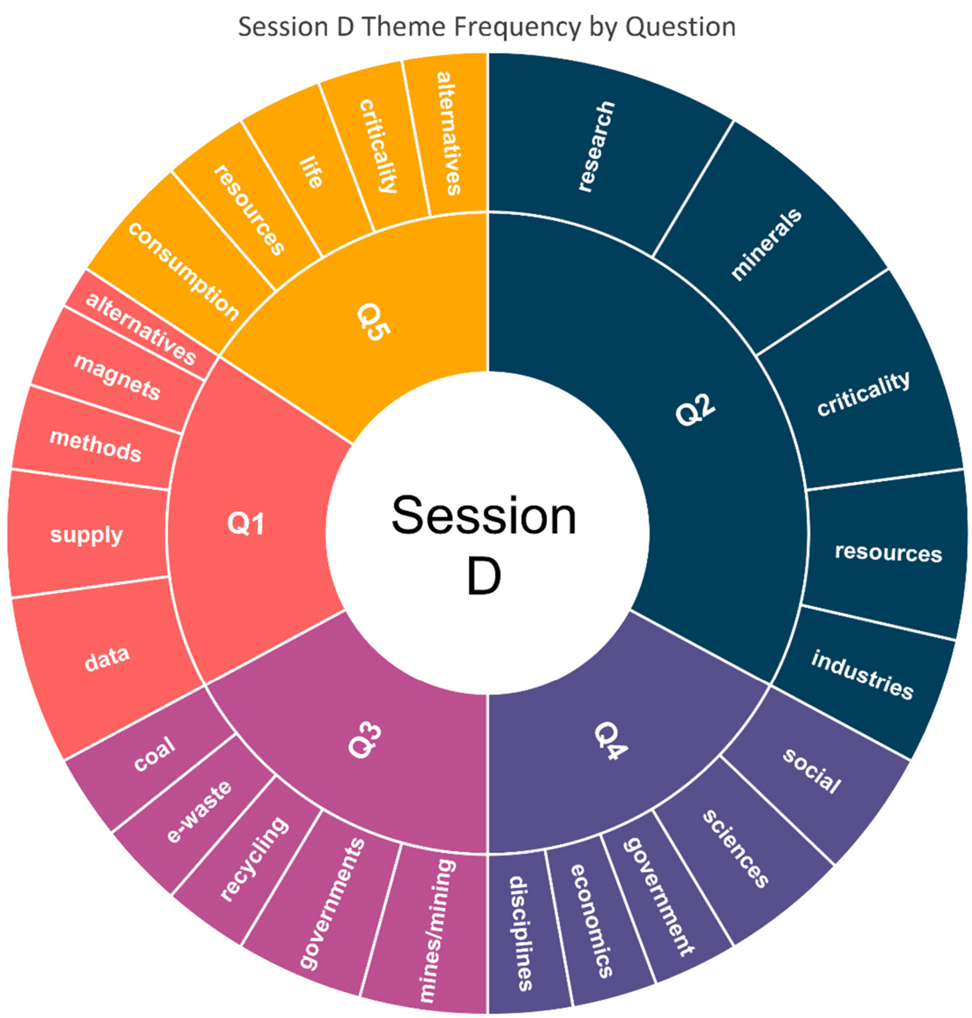

Figure 16: Top-5 themes mentioned in Session D: Technological Alternatives to Critical Minerals in response to the five questions asked during each breakout session. The size of each pie slice indicates the relative frequency of mentions. Q1: What are the roadblocks that affect the resilient supply of critical minerals? Q2: What are the most pressing research needs? Q3: What opportunities can lead to the fastest and biggest impact? Q4: What skills training is required to meet future workforce demands? Q5: What other questions should be asked, but are commonly overlooked?

5. Discussion of major themes

5.1 Overarching themes

As illustrated in Figures 4 to 16, several roadblocks were identified during the breakout sessions that limit critical mineral supply chain resilience in the United States. Five major themes were discussed during all breakout sessions, and thus are deemed most important. These themes include:

1. Insufficient understanding of domestic critical minerals resources. Workshop participants highlighted the need for more geologic research to identify new, and reevaluate existing, resources. Examples of research needs include extensive field mapping, comprehensive mineralogical/geochemical studies, and computational modelling to be used in mineral exploration. The workshop participants also highlighted the need for a qualitative and quantitative assessment of critical minerals that may be recovered as by/co-products from existing production streams, even if low concentrations currently prohibit economic extraction.
2. Technical limitations of current mineral processing and recycling technologies. Workshop participants highlighted the need for innovative mineral processing technologies to extract critical minerals from a wide range of materials, even if present only at low concentrations. Proposed research foci included more environmentally friendly chemicals/solvents and technologies with low energy demand. Participants also discussed the need for automated recycling technologies. The participants acknowledged the need for a centralized and simplified way to collect recyclable materials and incentives for the public to participate in recycling of appliances and e-waste.
3. Long permitting processes for mining and mineral processing operations, with often unpredictable outcomes. Workshop participants generally agreed that current policies represent a major roadblock for increasing domestic critical mineral supply. The development of new critical mineral-specific policies was suggested; major aspects included faster processing times and more transparent / predictable decision-making processes. The establishment of a new government agency that oversees critical mineral policies and associated activities was suggested.
4. The negative public image of mining and mineral processing operations. Workshop participants generally agreed that the negative public perception of mining associated activities remains a major issue. Public outreach and education initiatives were suggested as a measure, for example led by state agencies and/or academia and supported through federal grants. Participants also highlighted the need to include local communities in decision-making processes.
5. Limited availability of a critical minerals workforce. To address this issue, workshop participants suggested an increased focus on critical mineral specific skill training in higher education institutions, as well as advanced training of the existing workforce. The need for multi/cross-disciplinary skills training was emphasized, including, for example, geologic fundamentals, mining economics and policy law, metallurgy, and utilization of machine learning / Big Data modelling.

5.2 Themes specific to Session A: Mineral Exploration and Source Diversification.

A summary of the major themes discussed in Session A is presented here. All responses by the workshop participants are included in Appendix B.

Q1: What are the roadblocks that affect the resilient supply of critical minerals?

- Limited effective collaboration between government, mining companies, researchers, end users and local communities hamper mineral exploration and exploitation efforts.
- Strict state-level permitting and "Not in my Backyard (NIMBY)" policies and/or negative perception of local communities with regards to new mining operations.
- Poor characterization of domestic mineral resources and/or areas that are potentially prospective for critical mineral deposits.
- Recycling and recovery from existing production streams, including tailings, are complicated because of heterogenous and poorly characterized sources and a lack of adequate processing technologies (both for recycling/wastes as well as for recovery of critical minerals as low concentration byproducts of primary ore).

Q2. What are the most pressing research needs?

- Increase geologic knowledge of existing ore deposits and associated production streams / mine tailings, including abandoned mines that may contain critical minerals previously discarded as waste.
- Opening of new exploration space for critical mineral deposits.
- Research to promote feasibility studies for critical mineral recovery from extreme environments (e.g., deep Earth, oceans, space).
- Understand the mineralogical deportment of critical minerals in different stages of the supply chain, from ore to tailings.
- Increased funding for fundamental geologic exploration programs such as subsurface mapping.
- Identify pathways toward improving the negative public perception of mining activities.
- Understand the policy effect on critical mineral mining along the supply chain.
- Identify pathways toward economically viable e-waste recycling.
- Development of economically viable and environmentally and ethically sustainable extraction techniques for critical minerals from primary ore and secondary sources such as waste piles, mine drainage or tailing ponds.
- Development of innovative mineral processing/extraction techniques to account for changing demand of different elements.
- Improved knowledge of metallurgical processes in critical mineral recovery.

Q3. What opportunities can lead to the fastest and biggest impact?

- Improved and streamlined permitting processes, including limits on permit processing times.

- Develop policy to mandate that mines must report critical mineral endowment—even at low, sub-economic concentrates to aid the development of domestic critical mineral distribution models.
- Support of domestic smelters to strengthen the US market.
- Development of nickel, cobalt, and rare-earth element smelters in the US.
- Government incentives for the development of domestic critical mineral supply chains from cradle-to-grave.
- Develop automated, fast, and cost-effective ways to quantify the critical mineral potential of ore and secondary products.
- Government incentives and grants to support cross-disciplinary cradle-to-grave projects and collaborations between the mining industry and academia.
- Investigate existing samples / drill cores with cutting-edge techniques that were not available when the samples were initially taken.
- Develop 'machine learning' based exploration tools that utilize existing data sets by the mining industry and federal/state agencies.
- Incentives for mining companies to conduct domestic exploration and move their operations to the US.
- Community education grants to help overcome the negative image of mining operations.
- Funding of state surveys and local universities to do basic research and local geologic mapping, specifically focused on critical mineral potential.
- Mandate that university research is made publicly available and not hidden behind paywalls of for-profit publishers.

Q4. What skills training is required to meet future workforce demands?

- Cross-disciplinary training that allows for successful communication between geologists, engineers, metallurgists, etc.
- Chemical engineering principles.
- Recycling technologies.
- Economic geology / mineral resource geology principles.
- Basic geology, metallurgy and mining classes with increased emphasis on critical minerals.
- Mineral processing.
- Mine and refinery development strategies / management.
- Digital technologies (e.g., GIS, programming, Big Data).
- Subsurface modelling software.
- Analytical training that can be applied to critical minerals research (e.g., geochemical assaying).
- More emphasis on critical thinking and interdisciplinary skills.
- Qualitative and quantitative mineral assessment skills.
- Classis geologic training, such as field mapping.

Q5. What other questions should be asked, but are commonly overlooked?

- If critical minerals are so important, why are they not more expensive / subsidized?
- How can we improve estimates of the US critical mineral endowment?
- Why has the US lost so many smelters?
- What are the cut-off grades that allow for cost-neutral critical mineral mining?
- How do we get more people to recycle to make recycling a more viable critical mineral recovery alternative?
- What is the long-term plan for critical mineral mining in the United States?
- What are the environmental and health impacts of increased critical minerals mining and what are appropriate protective regulations?
- How can we reduce the need for critical minerals?
- What critical minerals can we recover from unconventional sources, such as brines and seawater?
- Should we provide more incentives for public education to overcome the negative perception associated with mining?
- What are emerging technologies that will affect what materials we consider 'critical'?
- Why do federal efforts seem to be increasingly restricting critical mineral recovery from public lands rather than encouraging it?

5.3 Themes specific to Session B: Supply Chain and Policy Issues

A summary of the major themes discussed in Session B is presented here. All responses by the workshop participants are included in Appendix B.

Q1: What are the roadblocks that affect the resilient supply of critical minerals?

- Uncertainties associated with permitting processes in the United States.
- Continuously decreasing size of a skilled to critical mineral mining workforce.
- Limited understanding of where critical mineral resources occur in the US, i.e., insufficient geologic characterization.
- General lack of interest in byproducts and lack of incentives to process critical minerals. Consequently, focus is almost exclusively on higher priced primary metals.
- Non-market forces (e.g., market manipulation, geospatial political tension).
- Small size of markets for several critical minerals.
- Uncertainties of forecasting demand for critical minerals.
- Limited supply diversification.
- Negative public perception of mining operations.
- Insufficient funding on the state-level to support geological surveys.

- Too many shifts in policies following each election.
- Lack of fundamental minerals research programs.
- Regulating agencies are missing the 'big picture'.
- Competing priorities of different regulatory agencies.
- Lack of support to scale-up research efforts in recycling, efficiency, etc.
- Reluctance to invest into mineral exploration and mining activities in the US.

Q2. What are the most pressing research needs?

- Machine learning and AI to support the development of better geologic models, critical mineral exploration and exploitation.
- New business models for recycling.
- Predictive modelling of where gaps may occur in the supply chain.
- Resolving knowledge gaps in environmentally and ethically sustainable mining practices.
- Improve technology/metallurgy to recover critical minerals from primary ore as well as other sources such as tailings and from recycling.
- Understand how to overcome the negative perception of mining.
- Constraining the deportment/distribution of critical minerals in different parts of the supply chain.
- Incentivize recycling and/or tighten regulations to increase recycling efforts.
- Development of innovative low energy critical mineral recovery processes for primary ores, tailings, recycling, etc.
- Identify and unlock the critical mineral potential of unconventional sources (brines, seawater).
- Identification of policies that can be put in place to improve critical mineral supply chain resilience.
- Geochemical fingerprinting of conflict minerals.
- Improve policies / processes for handling radioactive products associated with rare-earth element mining.
- Feasibility studies on establishing smelters near critical mineral supply chain routes in the US.
- Identification of potential substitute minerals.
- Quantification / forecasting of future industrial needs.
- Understanding barriers to e-waste collection and recycling.
- Inventory of the critical minerals that are discarded every year in the US.
- Quantification of energy needs associated with critical mineral recycling and reclamation and comparison to the amount of energy that can be generated with renewable sources.
- Identification of the social and physical infrastructural requirements to close the loop on critical mineral supply chains.

- Development of economically viable and environmentally friendly critical mineral recovery processes that can compete with US adversaries.
- Understanding where and how to gather critical minerals, including in extreme environments such as the deep Earth, oceans, and space.

Q3. What opportunities can lead to the fastest and biggest impact?

- Political backing on the federal and state level.
- Policy initiatives to support the critical minerals industry.
- Improved, transparent permitting processes.
- Targeted workforce development (e.g., student training, transitioning workers from similar fields).
- Strategic partnerships with allied countries.
- Adaption of existing techniques/infrastructure to accelerate critical minerals recovery.
- Expanding the National Defense Stockpile.
- Establishment of a federal entity specifically aimed at critical minerals.
- Improved recovery of critical minerals from existing production streams.
- Private/public co-funding for innovations and/or upscaling of existing technologies.
- Subsidizing critical mineral recovery from new sources and existing production streams.
- Government incentives to promote collaborative research between academia and the private sector.
- Update US mining code to better reflect challenges associated with critical minerals.
- Expand/adjust carbon tariffs to reward sustainable exploitation of critical minerals.
- Encourage/promote e-waste recycling, technically and through social awareness.
- Mandate redesign of future products in IT, automotive and communications sector to achieve optimal re-use and recycling of critical minerals.
- Promote domestic processing of critical minerals rather than exporting them to be processed by other counties.
- Government funding for not only TRL1-4, but also TRL 5 and higher.

Q4. What skills training is required to meet future workforce demands?

- Extractive metallurgy.
- Mineral / engineering economics.
- Data analytics, including Big Data.
- Mining, environmental and policy law.

- Communication / presentation skills.
- Soft skills and cultural/social competency to improve public outreach efforts.
- Life cycle assessment.
- Cross-disciplinary training including geosciences, metallurgy, mining engineering.
- Industry-supported student training initiatives for critical mineral related programs.
- International exchange programs to allow for global perspectives of the future workforce.
- Hands-on training of skills that meet future workforce demands.
- Geospatial analysis.

<u>Q5. What other questions should be asked, but are commonly overlooked?</u>

- How can we engage the mining industry more into the critical mineral discussion despite the low profit margins?
- How do we incorporate future critical minerals mining/recovery efforts into climate change models?
- How can we improve the public perception of the critical minerals sector?
- How do we measure the success of public education programs?
- How can we incorporate local artisanal mining efforts into larger scale / global models?
- What types of collaborations have the highest chance of success?
- Is national critical mineral self-sufficiency in a global market really an achievable and realistic goal?
- How can we establish more (and improve existing) mining engineering, metallurgical engineering and economic geology programs in the US?
- Why are we not recycling more?
- How can we keep corporations in the US rather than moving to cheaper locations overseas?
- Are we producing enough skilled workers to meet future workforce demands?
- Do we really have a workforce challenge considering that students are still looking for jobs?
- How certain are we that the critical minerals that we currently consider important remain important over the next decades?
- What are the logistical and infrastructural bottlenecks in critical mineral supply chains?
- What are the greenhouse gas emissions generated by establishing new mine sites and associated infrastructure?
- What alternative consumption patterns might reduce critical minerals demand?
- What elements would have the most significant environmental, economic and/or security impacts?

- What foreign countries can be considered reliable and responsible?
- What legislation and permitting requirements need to be updated to keep up with future demand?

5.4 Themes specific to Session C: Improving Mineral Recycling and Reprocessing Technologies

A summary of the major themes discussed in Session C is presented here. All responses by the workshop participants are included in Appendix B.

Q1: What are the roadblocks that affect the resilient supply of critical minerals?

- Insufficient recycling efforts (i.e., collection, processing of materials, recovery technologies).
- Lack of efficient and environmentally sustainable mineral processing and recycling technologies.
- Limited economic viability of critical mineral recovery during mining and recycling.
- Insufficient characterization of tailing and slag piles.
- Difficulties in forecasting short-, mid-, and long-term demand for critical minerals.
- Lack of appropriate policies at the federal and state level.
- Public perception associated with critical minerals supply.
- Current regulatory environment for mining and processing permits, including long processing times.
- Disincentives for efficient multi-mineral exploitation from a single site.
- “Not In My Backyard” attitudes toward critical minerals mining and processing.
- Lack of geologic understanding of the critical mineral endowment of the USA.
- Lack of smelters in the US which limits domestic critical mineral supply chain resilience.
- Poor understanding what amount of critical minerals can be recovered from existing production streams as byproducts.
- Lack of government support to incentivize critical minerals recovery.
- Pricing of commodities that may be vulnerable to global market manipulation.
- Insufficient critical minerals workforce.

Q2. What are the most pressing research needs?

- Improve knowledge of critical mineral processing from new resources, existing production streams and waste piles.
- Understand deportment of critical minerals along the supply chain.
- Decarbonization, including replacement of carbon as reducing agent for metal oxides.

- Add total material concentrations to end-user products analogous to nutritional facts in the food industry.
- Improve mineral processing / recycling technologies.
- Automated method processes for critical minerals recovery from e-waste.
- New methods to quantify the critical minerals present in heterogenous materials.
- Development of incentive strategies to increase recycling efforts, including product take-back.
- Improved metallization and refining technologies.
- Economically viable processing of coal waste and mine water for critical minerals.
- Scaling-up of promising technologies.
- Improved critical mineral recovery as byproducts from existing production streams.
- Public outreach efforts to overcome the negative perception of critical mineral mining / processing.
- Find substitutions for critical minerals and or develop technologies that reduce reliance on critical minerals.
- Specificity of adsorbents in solvent extraction and ion exchange processes.
- Implementation of a nation-wide recycling system.
- Innovative policy development to increase supply chain resilience.
- New regulatory framework on EPA laws to evaluate / access mine tailings.
- Critical minerals life cycle assessments.
- Assessment of environmental impacts of domestic processing and recycling.
- Financial cost-benefit analysis of critical mineral recycling (feasibility, profitability).
- Improve metal separation techniques for complex mixtures.
- Development of environmentally acceptable chemicals/solvents for metal extraction.
- Determination of cut-off grades that will make recycling economically feasible.
- Efficient separation of rare-earth elements.
- Reduced energy inputs in minerals processing.
- Developing data driven and/or AI-based processes optimization.
- Geologic mapping and characterization.

Q3. What opportunities can lead to the fastest and biggest impact?

- Development of end-of-life recycling technologies.
- Ban the export of scrap/wastes from the US to stimulate domestic recycling.
- Tax policies beneficial to the recycling industry.
- Policy changes and faster processing times.
- Enforce producer take back / extend producer responsibility.

- DLA purchase program.
- Improve mineral processing and recycling technologies.
- Better understand potential recycling sources (e-waste, old vehicles?).
- Government subsidies / incentives.
- Enforcement of fines.
- Tax incentives for social and environmental safeguards.
- Addressing public policy gaps.
- Public outreach programs to help overcome the negative perception of critical minerals mining / processing.
- Purchasing guarantees for critical mineral producers.
- National stockpiling.
- Mandate product design standards to allow for simpler future recycling efforts.
- Techno-economic analysis to inform technology development.
- Life cycle assessments to inform technology development.
- Machine learning / AI to accelerate and inform technology development / experimental design.
- Extraction of critical minerals from existing production streams and mine tailings as co/byproducts.
- Incentivize centralized consumer recycling.
- Proof-of-concept studies for recycling or reprocessing of highly dependent critical minerals.
- Understanding how reprocessing of mine waste, etc. can offset costs of environmental remediation.
- Development of a federal entity that oversees critical mineral recycling efforts.
- Increased funding for research, particularly academia-private sector collaborations.
- Funding for educational efforts / public outreach.
- Critical mineral workforce development.

Q4. What skills training is required to meet future workforce demands?

- Life cycle assessment.
- Circular economy.
- Interdisciplinary thinking and complex problem solving.
- Cross/multi-disciplinary skills training.
- Technoeconomic analysis.
- Chemical processing.
- Machine design.
- Environmental / sustainability aspects.
- Metallurgy.
- Resource characterization.

- Programming, machine learning, big data management / analysis.
- Field-based experience, e.g., geologic mapping, mining / mineral processing operations.
- Business management.
- Mineral economics.
- Thermodynamics.
- General leadership, social and teamwork skills.
- Safety training.
- Good STEM education, particularly at a young age.
- Professional continuing education for working professionals.
- Ability to work / communicate with a wide range or stakeholders.
- Conflict resolution skills.
- International relations.
- Statistics.
- Environmental law and mining regulations.

<u>Q5. What other questions should be asked, but are commonly overlooked?</u>

- Considering the workforce developments—what skills training will be obsolete in the future?
- What is the risk of some critical minerals no longer being deemed critical in the (near) future?
- What technologies can be employed to re-process old waste materials?
- How do we start the conversation with policy makers?
- What is the resource endowment above ground?
- Why is recycling not already being done more?
- Who stands to benefit—and who to lose?
- What can be learned from long-term success stories?
- What measures can be taken to have the private sector become more proactive?
- Should there be incentives to manufacture longer-lasting products?
- What products cannot be, or should not be, recycled?
- (How) can public-private partnerships be successful?
- Where should the public be disposing appliances for recycling?
- Why do some recycling centers request payments to recycle materials/appliances?
- Why does the government not provide incentives for recycling more?
- What is / should be the government's role in developing and subsidizing critical minerals mines and refineries?
- How can be build sustainable policies that overcome the election cycle?
- What is / should be the role of natural history museums and local non-profit organizations in increasing awareness of mining and public outreach?

- Should agriculture and mining be paired together?
- Do academics get enough funding for research?
- Are landfills a possible source for critical minerals?
- What long-term approaches can be developed to make this topical area move forward and succeed?

5.5 Themes specific to Session D: Technological Alternatives to Critical Minerals

A summary of the major themes discussed in Session D is presented here. All responses by the workshop participants are included in Appendix B.

<u>Q1: What are the roadblocks that affect the resilient supply of critical minerals?</u>

- Economic constraints
- No current alternatives to critical-mineral based magnets.
- Technological R&D is not driven much by supply issues.
- Insufficient funding for R&D.
- Unavailability of robust supply data.
- Identity diversity of sources.
- No efficient methods for critical minerals as byproducts from existing production streams and mine waste.
- Reduced energy and carbon footprints for US operations.
- Long permitting times.
- Absence of resource diplomacy.

<u>Q2. What are the most pressing research needs?</u>

- Supply-based research.
- Improved extraction methods.
- Research into a variety of alternative technologies to reduce dependence of particular minerals.
- To make technically feasible critical mineral recovery also economically viable.
- Identification and quantification of potential critical mineral resources.
- Program developments to increase the accuracy of geologic models.
- Research in recycling, including collection, dismantling and recovery.
- How to improve public policies.
- Public outreach to improve the negative perception of critical minerals mining and processing.
- Identify how the government can support the critical mineral industry in an efficient manner.

- Study European Union integration as a process of creating stable transnational supply chains.
- Consider resources outside of the USA.

Q3. What opportunities can lead to the fastest and biggest impact?

- Mine waste processing/reprocessing.
- Efficient recycling methods.
- Orphan mine liability.
- Improved collaboration/diplomacy between countries to stabilize regions and relationships to reduce criticality.
- Global governance on critical minerals.
- Quantify and adapt existing know-how and infrastructures to process critical minerals.

Q4. What skills training is required to meet future workforce demands?

- Life cycle assessment.
- Systems thinking / modelling large and multiple scenarios for decision making.
- Inter/multi-disciplinary skill training.
- Communication skills to allow interaction with a wide range of shareholders.
- Better bridging of social and natural sciences, as well as other disciplines.
- Critical thinking.
- Historical aspects of mining and economic consequences.

Q5. What other questions should be asked, but are commonly overlooked?

- Are critical minerals really critical?
- Are there alternatives to particular critical minerals?
- Do new products have to be better – or primarily more sustainable?
- Should life-cycle costs be part of economic considerations?
- How do we make the benefits of securing critical minerals accessible to everyone, e.g., jobs, goods, renewable energy solutions?
- What can we do with what we already have?
- Can we consider our high standard of living while talking about ecology?
- How robust are our predicted critical mineral demand curves for the future?
- Can we radically transform consumer patterns to account for limited critical minerals supply?
- Can we rethink basic assumptions and attitudes toward consumption of resources?

Appendix A: Workshop Agenda / Schedule

Workshop on Resilient Supply of Critical Minerals

August 2-3, 2021, 11:00 AM to 15:00 PM US Central Time

Online, via ZOOM

Hosted by Missouri S&T

Monday August 2:

11:00 AM – 11:05 AM	Opening Remarks (Marek Locmelis, O'Keefe Institute for Sustainable Supply of Strategic Minerals, Missouri S&T).
11:05 AM – 11:15 AM	Welcome by Missouri S&T Chancellor (Mo Dehghani, Missouri S&T).
11:15 AM – 11:45 AM	Keynote lecture: The implications of technological innovations for critical mineral supply chains (Thomas E. Graedel, School of Forestry & Environmental Studies, Yale University)
11:45 AM – 12:15 PM	Keynote lecture: The critical mineral potential of the United States and USGS efforts to facilitate new mineral resource discovery (Thomas C. Crafford, Warren C. Day, Michael J. Magyar, National Minerals Information Center, U.S. Geological Survey).
12:15 PM – 12:45 PM	Keynote lecture: Critical mineral resources and the challenges to providing them into America's supply chain" (John Uhrie, Doe Run Company).
12:45 PM – 13:15 PM	Keynote lecture: Global rare earth politics: A pathway forward (Julie M. Klinger, Department of Geography and Spatial Sciences, University of Delaware).
13:15 PM – 13:30 PM	Break
13:30 PM – 14:45 PM	Breakout sessions A. Mineral Exploration & Source Diversification: Identify Research Needs B. Supply Chain & Policy Issues: Identify Research Needs
14:45 PM – 15:00 PM	Summary of breakout sessions / wrap-up Day 1

<u>Tuesday August 3:</u>

11:00 AM – 11:05 AM	Opening Remarks (Marek Locmelis, O'Keefe Institute for Sustainable Supply of Strategic Minerals, Missouri S&T).
11:05 AM – 11:35 AM	Keynote lecture: USGS' material flow modeling that it uses for criticality assessment and the role of recycling and reprocessing in determining criticality (Nedal T. Nassar, National Minerals Information, Center, U.S. Geological Survey)
11:35 AM – 12:05 PM	Keynote lecture: Where have all the smelters gone? America's dependency on foreign non-ferrous metal production (Michael Moats, O'Keefe Institute for Sustainable Supply of Strategic Minerals, Missouri S&T).
12:05 PM – 12:35 PM	Keynote lecture: The Illicit Economy and the Role of Critical Minerals (Jon J. Kellar, Department of Materials and Metallurgical Engineering, South Dakota School of Mines and Technology).
12:35 PM – 13:05 PM	Keynote lecture: Mineral resources for the energy transition: research needs for assuring resilient supply chains (Roderick G. Eggert, Critical Materials Institute, Colorado School of Mines).
13:05 PM – 13:20 PM	Break
13:20 PM – 14:45 PM	Breakout sessions C. Improving Mineral Recycling & Reprocessing Technologies: Identify Research Needs D. Technological Alternatives to Critical Minerals: Identify Research Needs
14:45 PM – 15:00 PM	Summary of breakout sessions / wrap-up Day 2

Appendix B: Compilation of comments from each breakout session

SESSION A: Mineral Exploration and Source Diversification

Question 1: What are the roadblocks that affect the resilient supply of critical minerals?

- Strict state level permitting of mining operations.
- Government, mining companies, end users, and researchers. Without effective collaborations and coordination, it's difficult to make progress. The literature has been making the same suggestions about collaboration between.
- Often low concentration in ores and byproducts, so they are not reported in mine permits, which really complicates understanding the geologic endowment of different deposits. A lot of the heavy lifting is already done.
- Recycling isn't going to be able to supply significant amounts of many raw materials until their end of life, which will be awhile yet for PV, wind, and other technologies with long useful lives.
- Many critical elements are found at ppm or ppb levels in natural sources, thus they are not routinely examined during coring operations.
- Recycling is difficult because of heterogenous sources and diverse supply locations.
- Uncertainty in the permitting process hinders investment in mining, smelting, and refining.
- Material flows.
- There are sources, especially from waste streams, but we lack adequate processing capacity.
- With respect to reprocessing mine wastes, liability for the residual waste that would be left behind even after reprocessing to extract critical minerals.
- In terms of production: To what extent can we repurpose abandoned/unused processing facilities to help meet our needs for critical mineral production.
- No investments into domestic exploration.
- NIMBY—for exploration/opening mines.
- Poor understanding of regional geology applied to the resource potential.
- Poor perception of mining efforts in local communities.
- State governments need to increase universities' funding to support research of benefit to the community.
- Leading to limited models/understanding of deposits.
- Mapping is now done only on the surface—not subsurface mapping like Australia's UNCOVER project.
- Limited collaboration/matching datasets across state boundaries.

- Lack of infrastructure to process ore and need more research to process coal drainage and waste.
- Aside from politics and geologic location, the main will be access to extreme environments.
- Long, complex permitting process for new mines.
- Insufficient knowledge of resources.
- Permitting difficulties apply to processing and refining facilities, too.
- Lack of critical mineral recycling.
- Knowing where they are, could come from.
- Recovery of critical minerals that are by-products of the recovery of major minerals. By-product minerals are so controlled by the economics of the recovery of the major commodities.
- There are still places with limited geological studies.
- Mining companies need to meet the bottom line of economics (generate net revenue) but the prices of critical minerals don't justify pursuing them.
- Bad government policy in developing countries.
- Critical minerals are often a by-product of mining other metals and it can be hard to optimize the process flowsheet for them over the economic drivers.
- Low enrollment in USA schools.
- Bad public image for mining related programs and activities in the USA.
- One major roadblock that affect the supply of critical minerals is the timeline of government policy which delays granting of permit to mining firms in USA.
- Minerals due to absence of investment over past decade and/or demand that exceeded production. Personnel resources—are we placing enough interested students in positions.
- Lack of samples.
- Domestic processing plants for ore extracted from domestic ore deposits.
- Understanding how/where they are concentrated (particularly for byproduct/coproduct).
- General public disinterest in mining (even just sand and gravel).
- Long approval process for owners of deposits to actively mine.
- Recycling of e-waste is technologically and economically unfeasible today.
- From my perspective is one big roadblock is access to capital or grant-public funding for exploration…you can't increase supply until you find it!

Question 2: What are the most pressing research needs?

- Getting feet on the ground to sample the abandon miners and the dump piles, and the manpower to do that. We have over 13,000 mines and many in the western side of the state need to be looked at for REE's and other.
- Has weathering changed the kinds of metallurgical extraction processes that can be applied to wastes? Sulfide ores may not be sulfides anymore after several decades. What are the mineral hosts of the valuable components?

- I think mining has a big challenge in changing "Joe Plumber's" mind that mining is a dirty, polluting industry. It's not a research need, but I think it is essential to move forward with developing domestic supply chains.
- E-waste recycling needs policy support.
- Design battery based chemical processes of recycling.
- Where (mineralogically) are the critical elements in wastes (tailings, slags, residues, etc.)?
- Understanding the policy effect on mining critical mining.
- Identification of critical element loses in existing metal supply chains and methods to recover these elements from those chains.
- How do we encourage the recycling of more e-waste?
- Are social justice and mining incompatible?
- What is the value of all elements in ores and wastes—is it worth going after wastes as a resource? Is there enough value to go after these materials without the primary commodity driving the economics?
- What factors control critical element enrichment in ore forming environments. Has important implications for resource quantification, exploration, and possibly recovery.
- How would critical minerals recovery from waste concurrent with remediation efforts actually affect overall project costs? I think there is a sense that recovery could offset remediation costs, but I wonder if that is actually the case.
- Is e-waste recycling hindered by metallurgical barriers? Especially due to the heterogeneity of the materials?
- Location of deposits and processing.
- Funding for research and research infrastructure in academia by federal and industrial sources.
- Critical element deportment and inside the mine gate processing/recovery research.
- Secure and sustainable materials processing.
- Environmentally safe extraction of critical minerals from waste piles or tailings ponds.
- A forward need to include better communication between engineers and scientists.
- Opening of new exploration space on Earth and beyond.
- Research to promote feasibility studies for exploration and mining in extreme environments (deep Earth, ocean, space).
- Develop technologies to dig beyond 4-5 thousand depth.
- Recycling of existing materials.
- The need to replace critical materials with new non-critical materials.
- Selectivity of resins and solvent extractants following leaching or their use in water and wastewater treatment.
- The need to design commodities for recycling.

- The need to recycle.
- Developing economically viable methods for extracting REE's from mine drainage and coal waste.
- How do we explore and mine sustainably and considerately of social justice issues.
- Comprehensive and reliable national scale data (at a reasonable resolution) on critical mineral distribution.
- Delineation and characterization of critical minerals in existing mine waste at legacy mine sites.
- Better understanding of where and how by-product critical minerals occur and in what types of ore deposits.
- Study of where critical minerals occur in wastes at operating mines.
- Environmental impacts/toxicity of the new universe of critical minerals. There's been little study of their environmental impacts, and where and how they're released to the environment, and in what quantities.
- Study of where by-product critical minerals occur and are not being recovered at operating mines.
- Better understanding of fluid-rock interactions that control the distribution of critical minerals.
- Research showing that investment in government-supported R&D is critical for meeting domestic needs.
- This might only apply to a handful of elements—many elements have well studied toxicological effects (to a degree).
- Processing techniques for recovering by-product critical minerals.
- Development of low capital cost processing options
- More funding should be allocated to mining and minerals related programs to boost research interest in the field.
- More funding for exploration campaigns.
- Recycling waste in abandoned mines.
- Recycling flowsheets can be different than those from ores/tailings and have other threats/opportunities associated with them.
- Cobalt Missouri idea.
- Extraction/separation processes or alternatives to conventional separation processes. How will product development affect needs…e.g. what will be the components.
- Funding for new coring programs to recover deep samples.
- Large enough sampling to have some left for later.
- Understanding ore formation, incorporation of critical elements into primary minerals.
- Ways to streamline or support comprehensive mining of byproducts with the primary products. Many critical commodities are by-products.
- Understanding basic partitioning of elements in ore-forming fluid.

- To improve the knowledge of the metallurgical process in order to understand better how to recover the critical minerals in already known deposits.
- Elements, thermodynamic partitioning constants are not well known—basic studies of these partitioning constants would help to understand ore formation, behavior during processing, and behavior once in.
- Document and map private research finds, or to partner with private sector for exploration research. And USGS can't document it unless our state geology dept is involved. Public funds need to be available to help.

Question 3: What opportunities can lead to the fastest and biggest impact?

- Policy and/or permitting change at state levels.
- Set a limit on permitting process time.
- A demonstration project on critical mineral extraction and recycling.
- Use Title III funds to target REE production.
- Seems like the biggest, fastest input would be something driven by government policy.
- Create a policy to force mines to report critical element endowments in JORC or NI-43-101. But don't assign a value to it. Then we could at least know what critical elements are where.
- Clear policy on what to do with thorium released during REE policy.
- Support currently operating smelters and target the develop of REE and Ni-Co smelters.
- Investment by the government or enable environment for financial investment from private companies such as policy improvement.
- Government spends a few billion dollars and develops an entire REE supply chain.
- Some fast way to quantify value in ore and wastes, ID materials with potential and not spend any more money thinking about recovering critical minerals from the rest unless the economic situation changes.
- Combining academic and industry.
- Investment into the rare earth industry development and cleaner processing technologies.
- Identifying grade of critical minerals in active mine streams.
- Some of the highest REE concentrations are associated with AMD wastes. Environmentally sustainable extraction of critical minerals from these wastes must be coupled with reclamation/remediation of these sites.
- Mine waste piles and acid-mine drainage (ponds) are readily available, and reprocessing them could have a greater impact than just production of critical minerals.
- The amount of carbon that can be absorbed (via mineralization) during the reprocessing of these waste streams and other environmental benefits.

- Outsourcing mining and extraction to other countries is coming back to bite the US.
- Defunding the Bureau of Mines, closing of Minerals Engineering and Mineral Exploration programs in Academics are good examples.
- From the potential remediation of these existing liabilities could be very significant.
- Cross disciplinary research that rewards cradle to grave projects.
- Education, training, and internships for the students who will be the future workforce/researchers.
- Including machine learning into exploration strategies.
- Take advantage of existing data set for exploration.
- Our government may need to subsidize at least the most critical of the critical materials.
- Communication between communities, companies and law.
- And policy makers.
- Incentives for mining companies to conduct domestic exploration and move their operations to the US for critical minerals.
- In addition to "machine learning", increased study and use of robotics and process instrumentation and control for safety purposes as well as increased recoveries/grades.
- Community education grants.
- Encourage projects that include local communities to overcome the negative perception of mining.
- Incorporating local communities/stakeholders at the start of projects.
- Cross-disciplinary is a great answer. A current example is "geometallurgy" but that is a dual discipline.
- The future process engineer will need to understand not only geology and metallurgy but also machine learning, data management, robotics, instrumentation, and control, etc.
- It’s going to be multi-disciplinary.
- Is there an "opportunity" that leads to shorter lead times for permitting of mines and/or smelters?
- Focused research on characterization and recycling of e-waste and electronics waste.
- Massive exploration for minerals in the USA.
- Importation of ores from developing African countries.
- More funding to research on critical and strategic minerals.
- Fastest—has to be both in the recycling and manufacturing materials to aid in recycling. Biggest?
- Development of new technologies for exploration.
- Financial incentives/subsidies for multiple commodity mining that includes critical commodities is one opportunity.

- Funding vis USGS/Department of Interior to both public and private companies dedicated to exploration research, or R&D on critical mineral processing technologies. Funding direct without having to go through another.
- Funding state surveys and academic to do basic research and mapping on critical mineral distributions that can be shared publicly.
- Cooperation between government and industry and academia.
- Decrease approval time for deposits to actively mine.
- Also note the pending "infrastructure" bill in Congress supposedly has set aside some dollars for critical mineral research and related supply incentives…not sure of specific details but this is a timely topic.
- Focus of processing waste streams from either coal or hard rock mines.
- Make academic research more easily accessible and targeted, open source and not behind a paywall, especially when government-funded.

Question 4: What skills training is required to meet future workforce demands?

- Chemical engineering principles.
- Recycling technology, metallurgy of e-waste recycling, evaluating wastes for extraction, methods for extraction from wastes, environmental chemistry, financial modeling, metallurgy, micro-scale characterization.
- Economic geology, mineralogy, analytical chemistry, mining, life cycle assessment, mineral processing, metallurgy, environmental science and engineering, entrepreneurship.
- The basic geology, metallurgy, and mining classes with the addition of a more focused emphasis on REE's and critical minerals, along with recycling. Classes that focus on policy making and permitting with in the mining industry, etc.
- Mineral processing and refinery construction and management.
- Larger academic supply for mining and engineers and geologists.
- Mine development strategies.
- Mineral processing and mine safety training.
- Supervising agency that helps moderate the future workforce.
- We need to train more skilled engineers and scientists.
- We need to train engineers to talk to scientists and vice versa.
- Training that covers traditional and new digital techniques (e.g. GIS, programming, big data) to develop multi-disciplinary skills.
- Company incentives for workforce development.
- Incentives to train the next generation of researchers.
- Better implementation of skillsets related to critical minerals research into curricula - same key components for all universities across the USA.
- Redesign of existing curricula to include skills and training needed for the future.
- Too different focuses in different parts of the country dilute the overall strength of US education.

- Multidisciplinary and crosslinked education—an example: BS in metallurgical engineering, a MS in electrical engineering, and PhD in a different subject, or dual BS degrees.
- Reward universities that conduct applied critical minerals research and train a workforce the same way that companies are rewarded.
- Cross training between geochemistry/geology, mineral extraction, and materials science.
- Whew. Geology mineral processing, mine engineering, miners, chemists, physicists, GIS, numerical modeling, and a lot more.
- Subsurface modelling software (Leapfrog, ML) and analytical instrument training (ICP-MS, ICP-OES).
- More exploration in space.
- To me it's less about skills needed for mining/processing (given there are enough people) and it's more about understanding/mindset needed in policymakers and manufacturing.
- Critical thinking skills, interdisciplinary skills.
- Geochemical analysis/assaying.
- Exploration thinking. Resource assessment methodologies.
- Interdisciplinary word skills, and data analysis.
- Geostatistics: i.e. data interpolation and geologic resource modeling.
- Exploration—more traditional geology and economic assessment training coupled with new geochemical modeling education—one example is models offered by MagmaChem Exploration.
- Positive interactions with stakeholders and the public.
- Quantitative and qualitative mineral assessment skills.
- Classic economic geology training, such as alteration mapping.

Question 5: What other questions should be asked, but are commonly overlooked?

- If critical minerals are so important, why are they not more valuable?
- How can we improve estimates of geologic endowments of critical elements at current deposits to improve resource estimates?
- Why has Japan, Korea and the EU maintained their smelting and refining capacity and the U.S. hasn't?
- Do you think old mines and processing plants were operated so inefficiently that they threw away lots of values which we can now capture by processing tailings and wastes?
- What are cutoff grades where critical elements become cost neutral to extract? I wonder if there would be other ways to generate the capital investment to build a critical element recovery circuit.

- We know we need to recycle more e-waste but how to do involve the public to make this happen more often? How do we get people to recycle instead of "tossing it out?"
- What are the economic conditions that would make mines or governments act to recover critical elements?
- It's not really overlooked, but the sound economic analysis of the opportunities that are available are necessary to prioritize the potential options.
- Oversight agencies.
- What is the plan? For every complaint about what to stop doing/mining, there must be an option for the time after. Carbon free is great, but where is all the energy coming from and the commodities to support that?
- Carbon free is great, but where is all the energy coming from and the commodities to support that?
- The human side—expanding mining to meet demand means more land required/changing technology may mean fewer miners required (robotic technologies). Displaced people will need support too.
- What are the environmental and human health impacts of the increased consumption of critical minerals?
- How can demands for critical minerals be reduced?
- What are appropriately protective environmental regulations? Are there areas where environmental regs are unnecessarily proscriptive, and where alternative regs would be appropriately protective, but less burdensome to mineral recovery?
- No answers for Moderator 5 - Session A - Question 5.
- What critical minerals can we get from brines or other subsurface fluids? Seawater?
- How can we increase the recycling of critical commodities?
- Should we provide more incentives for public education about mining and critical minerals? The word "mining" is seen by many in the public as a bad word due to industry practices 50-100 years ago.
- What are some emerging technologies that might change the focus of critical element's need in the future?
- Bipartisan effort to increase domestic supplies of critical materials, why is Congress and Biden administration trying to nearly double the amount of federally managed lands that would be off limits to mineral exploration or timber.
- Why is there not a requirement to document critical mineral resources on public lands before they can be locked up and prohibited from mineral exploration by congressional acts?
- What are the impacts of increasing domestic mining of critical minerals (for many, environmental behavior and impacts are largely unknown). And how to mitigate.

SESSION B: Supply Chain and Policy Issues

Question 1: What are the roadblocks that affect the resilient supply of critical minerals?

- Permitting: Uncertainty associated with permitting in the US.
- The increase in mineral usage and decrease of available skilled labor in the industry.
- Limited understanding of where resources occur (geological characterization).
- Lack of interest in byproduct metals, when the primary metal has a much higher value.
- Nonmarket forces—e.g. market manipulation by government and other actors.
- Small size of the markets—link to technological uncertainty on the demand side - not much room for multiple producers.
- Uncertainty in the critical minerals market, e.g., what battery technology will be critical and therefore which markets will be dominant to justify investment.
- Lack of supply diversification—by definition, a single source makes the supply chain not resilient.
- Negative perception of mining in the broader US society that affects ability to attract talent into the space to drive innovation.
- Lack of skilled labor—geologist (state geo surveys).
- States don't have enough funding for geo surveys.
- Are we assuming from a domestic (US) perspective only?
- Delays in permitting.
- Geospatial Tensions/motivations.
- Costs are "too high" for local miners.
- Poor public perception of the need for mining.
- Elections every 4 years and shifts in policies.
- Gap between industrial practice and policy formulating agencies. Regulatory authorities are in different phase then what industry seeks. Both are correct at their respective phases.
- Lack of fundamental minerals research (loss of USBM and NSF programs).
- Returns (e.g. prices) are "too low".
- Joint workshops including academics, industry, and regulatory heads will help bring people at one page.
- Regulating agencies are missing the bigger picture.
- Competing priorities of various regulatory agencies. Setting requirements that are too high to meet on one hand while wanting to be a global leader on the other hand.
- A few years ago, most downstream RE users did not understand the supply chain problem. Now they know more but are not paranoid enough about the urgency of the issue.

- Understanding where we get critical minerals from co- and by-product associations.
- Lack of support to scale up research breakthroughs in efficiency, recycling, etc.
- The interests of the public conflicting with best interest and long-term sustainability.
- Lack of geologic mapping coverage for many areas in the US.
- Data—specifically free and public information.
- Public perceptions of mining.
- Public pushback due to misunderstanding the benefits of mining.
- Size of critical minerals sector; often of limited interest to major mining companies.
- Lack of public knowledge of importance of mining, smelting, and refining.
- Political instability in source countries.
- Reluctance to invest.
- Lack of social and environmental safeguards makes operations more likely to encounter community resistance.
- Lack of up-to-date regulatory requirements for newer mining technologies.
- Lack of policy coordination and mandates to support scaling up circular economy.
- Restrictions that make it difficult to recycle used products.
- Permitting process uncertainty.
- Lack of public investment rebuilding the mid-stream firms: It's one thing to facilitate mine permitting, but quite another to ensure there are buyers with know-how to do things with mine outputs.
- Lack of knowledge of potential value add on critical minerals to mining operations.
- Understanding (quantifying) future demand for various elements.
- Identification of economic deposits.
- Regulatory and permitting issues.
- Metallurgical extraction processes that are environmentally friendly and more efficient.
- Geographic concentration of the REE mining and downstream processes.
- Incentives to process materials.

Question 2: What are the most pressing research needs?

- Machine learning and AI to increase economic feasibility of smaller deposits of necessary minerals.
- New business models for recycling—not always economic (especially for collection) so what business models can incorporate these challenges.
- Anticipating where major gaps might occur in the supply chain.

- Resolving knowledge gaps in sustainable mining practices to reduce near mine impacts (better reclamation, etc.).
- Developing standards for "green" minerals that are transparent and "usable".
- Machine learning and AI coupled with models of ore genesis to Identify potential resources.
- Increasing program development to increase accuracy of geologic models.
- Technology/metallurgy to extract minerals from tailings.
- Understanding how to effectively communicate the contribution of minerals to sustainable development to high school students, voters, and public at large. More difficult to convince younger audience.
- Understanding department/distribution of critical minerals in base metal supply chains
- Incentivize recycling or tighten regulations.
- Developing processes for primary production and recycling that are less energy and chemicals intensive—and thus reduce both costs and environmental impacts.
- Unlocking unconventional resources.
- Identification of critical minerals critical for US (dedicated resources for specific minerals instead of overall general research).
- Parts recycling how-to.
- What type of policies to put in place.
- The need for track and trace of conflict/critical minerals from ore to mineral concentrate to metal to component.
- Step wise scaling up reliant on countries nearby following by going broad.
- Better processing/better mineral recovery processing. Also, recycling technologies to reclaim minerals from waste streams.
- Radionuclides in the basic ore stream, especially Monazite (U, Th), tends to be a show-stopper, unless located next to a DOE/NRC licensed facility. So the US needs a new regime for handing, processing of RE minerals.
- Designing of electronics for recycling. Regarding the "what policies" could be encouraged by a recycling requirement on major electronics.
- Feasibility studies on state/federal sponsored smelting districts nearby localities on current supply chain routes for ore concentrate going out of US.
- Short term sustainable, efficient, safe and mobile processing technologies for small body deposits.
- Urban mining (including old dumps).
- Mandate that firms publish their specs so researchers can answer these questions. They don’t have to disclose all their secrets if they publish their inputs/volumes!
- Mineralogy, geometallurgy and mineral processing.
- Material Flows - to understand where smelter and refinery critical metal comes from and how it can be enhanced.

- What do successful cases of frontline community engagement actually look like.
- Better understanding of needs and concerns of communities near high-potential deposits.
- Potential substitute minerals.
- Geochemical /mineralogical/geophysical analysis of source rocks for potential REEs and other critical elements.
- New or modified methods of extraction and processing to reduce environmental impact.
- Quantifying industrial future needs.
- How much is the transition actually going to cost? How does this compare to, say, fossil fuel subsidies.
- How many metric tons of critical minerals are in, say, soon-to-be obsolete oil and gas pipelines.
- Recycling of complex alloy.
- Wealth from waste—competing circular economies.
- Make garbage research sexy—get more people into figuring out how to recycle our current materials.
- Understanding barriers to e-waste collection and recycling.
- Waste product analysis for potential recycling and reuse options (i.e. coal ash, mine tailings, etc.).
- Need fine resolution of waste streams for GIS (by element/mineral/component).
- What are the energy demands for recycling and reclamation, and how much of these can be met with renewable sources (ideally scaling up over time?)
- How many of each critical mineral do we discard annually? We need an inventory of the resources hiding in our garbage!
- What are lithium-ion battery waste steams?
- What are the social and physical infrastructural requirements to actually close the loop on critical mineral supply chains? Literally: How do we collect e-waste etc. and get to it facilities to recycle it, and where are those facilities located, and what laws are needed to support this?
- Incentives for corporate disclosure and/or R&D development.
- Determining how to separate chemicals and minerals from each other.
- Systems analyses—like LCA TEA—are very important.
- Environmentally friendly more efficient processing.
- Process integration.
- Economical and environmentally friendly process that can compete with Chinese production.
- Co-production opportunities need to be evaluated.
- Identifying where and how to gather critical minerals (i.e. like extreme environments).

Question 3: What opportunities can lead to the fastest and biggest impact?

- Political backing: Positive discussion of mining on a national level would help raise funds and interest in mineral extraction and research.
- Policy initiatives that support the critical minerals industry.
- Increased student research and Involvement.
- Retraining those who are shifting from other Industries (coal) into critical minerals to address short term workforce needs.
- Expanding the National Defense Stockpile.
- Partnering with allied countries.
- Adaptation of existing technology know-how and established infrastructures to accelerate the transition.
- Active evaluation of innovations developed in the past but not fully commercialized
- ARPA-E-like entity aimed at material supply chains.
- Technologies that make extracting critical minerals as by- or co-products of existing supply chains profitable.
- Technologies that make extracting from waste streams (tailings, etc.) profitable and sustainable.
- Private/public co-funding for scale-up testing of innovations demonstrated at laboratory scale (mineral processing and extractive metallurgy for both primary production and recycling).
- A reinvented US Bureau of Mines!
- Dedicated research at one place! Instead of spreading money around different universities.
- Reinvent US Bureau of Mines.
- NSF did away with a dedicated minerals processing/extractive program about 1992, with that went fundamental research in this area. The program should be brought back.
- By comparison, I've been told that the government of China puts about.
- Improved (clear) permitting processes.
- Redirect fossil fuel subsidies (in the hundreds of billions of dollars annually, ~80% of all energy subsidies globally) to renewable critical mineral supply chain research and deployment.
- Mineral processing: see Te extraction plans at Bingham Canyon for example, where Te already being mined but deporting to waste is now going to be extracted (at a profit). Also Li at Borax, CA.
- Process simplification and reduced embodied energy for feedstocks.
- Government grants/incentives to increase company involvement.
- Understanding mining and processing waste, unlocking the critical metal (and environmental) value in this problematic material.

- Mainstream ILO 169 (Free Prior and Informed Consent) as part of an update to US mining code.
- Identify existing research breakthroughs in critical mineral sustainability research that can be sped-up for rapid and wide-speed deployment.
- Preemptive incentivization of specific markets to ease stresses on infrastructure.
- Expand/adjust carbon tariffs to reward sustainable exploitation of critical minerals.
- Make e-waste recycling easy—this requires building out local infrastructure.
- Looking at current operations waste streams to identify potential products that could be extracted.
- Change consumer expectations about e-waste, so consumers demand products that are built to be responsible through their entire life cycle.
- Public education campaigns.
- An Xprize for a viable lithium-ion battery recycling model?
- Mandate full redesign for re-use and recycling by 2030 for all IT, automotive, communications sectors (scientific and medical instrumentation can have, say, another decade or two).
- How can we make recycling a public service, so it isn't held back by cost constraints?
- Evaluation of mine waste for opportunities.
- Policy issues.
- Development of downstream value added REE processes in Mountain Pass.
- Processing materials in-house (within the country) rather than relying on exporting materials to other countries (China).
- Giving businesses and people incentives to recycle/process critical materials.
- Funding for TRL 5 or higher. Typically government funds to this level, but then relies on commercialization but there is not commercialization to speak off.

<u>Question 4: What skills training is required to meet future workforce demands?</u>

- Extractive metallurgy.
- Mineral economics.
- Data analytics.
- Basic understanding of the industry.
- Statistics, econometrics.
- Engineering economics/TEA.
- Promote mining law and Environmental Policy/Law courses for other disciplines (e.g. political science, international affairs).
- Soft skills, ability to understand the environmental and social implications of mining.
- Ability to handle large data sets and communicate them effectively.
- Communication, presentation, and writing skills.

- Ability to engage broadly with stakeholders.
- Ability to innovate, move things along the TRLs (technology readiness levels).
- Life cycle assessment.
- Life cycle thinking.
- Promote multidisciplinary and analyze the issue from different perspectives: academic, political, and industrial.
- Systems-thinking—people can get tunnel vision, but they need to focus on the actual problem.
- Lots more geology majors who study mineralogy and crystallography! And metallurgy!
- Companies need to invest in mining/minerals/extraction programs for the long haul.
- Ability of instructors, influencers, and other stake holders to incite interest about mining and associated fields. Incorporation of programming and computer science related course.
- Interdisciplinary approaches.
- Cultural/social competency, ability to work with diverse people.
- Prepare future leaders to effectively engage local communities and diverse stakeholders.
- Broaden international exchange programs so workforce has global perspective to meet global challenges.
- Leadership—listening, communication, social.
- Multi-dimensional problem interpretation and solving—to get technical experts to think about social, political, and ethical etc. dimensions of problems with "widgets".
- More university opportunities to teach about mining and material sciences.
- Not always broadening an individual's knowledge, but teaching them to compliment other's knowledge base.
- Land-based education so workforce sees land as more than its geological endowments.
- Scientists in the critical minerals industry should understand risk and economic impacts.
- Cross-disciplinary and cross-sector training so that people are versed in technical, environmental, social, economic, and political dimensions of critical mineral sectors.
- Understanding of environmental, social, and governmental challenges to mining and critical metal supply.
- Geos need to learn more about the economic impact.
- Hands-on-training—moving beyond reading books and lectures.
- Improve knowledge of the importance of mining at K-12 to get more people into geology, mining, engineering etc.

- Geography and geospatial analysis, community engagement, complex problem solving.
- Geology (especially geochemistry, geologic mapping, geophysics, structural) and its importance to the future of critical minerals.
- Environmental policy training.
- Systems thinking.
- Understanding of chemistry, geology, and metallurgical processing.
- Understanding and effectively using systems analyses.
- Data analytics and deep learning.
- Big Data—statistics.
- Process modeling and simulation.
- Programming and other skills to let the computers do the work for you—AI and robotics.

Question 5: What other questions should be asked, but are commonly overlooked?

- I find that the mining industry is not engaged enough in these discussions. Exploration expenditures don't reflect the pressing nature of this issue. How do we engage the industry in this?
- Climate change tends to drive these conversations. But the impacts of mining tend to be very local and potentially harsh. How do we incorporate local/near-mine impacts in these assessments?
- How do we use techniques that we use today and plan for "tomorrow".
- How can we market the industry as a whole to better public perception and increase interest in the mining workforce?
- Small scale and artisanal mining are not talked about enough in these discussions given their higher environmental impacts. How do we incorporate that sector more formally?
- What types of collaborations work best in solving some of these concerns?
- Intermediate products of mining (concentrate, metals, alloys, etc.) need customers. Many of the customers these days are outside the United States. National self-sufficiency in the entire supply chain is an unrealistic goal. What is the real goal? Because global supply chains exist because they have advantages so can we focus on risk?
- How can we improve public perception/interest in the mining industry? Natural history museums?
- The strength of the mineral programs is not discussed enough (13 mining engineering, 17 metallurgical engineering, very few economic geology).
- Why don't we recycle more? It is a technical or social challenge, or both?
- Is the US afraid of China or does the US want to build its own resilience?
- Corporation moving value addition overseas to maximize profit.

- Many people seem not to know the basic history of modern mining and materials. How did we get here? We're way past the Iron Age…but many don't get that point.
- Do we really have a workforce challenge? Students are still looking for job…placement is good but I don't sense that there are too few students currently.
- How certain are we that the critical metals we think will be important in the next 30-50 years are actually going to be important; the role of changing tech, etc.
- Better, richer forecasting and "future studies".
- What are the logistical and infrastructural bottlenecks to mainstreaming the circular economy?
- What do we really need to extract and/or process in country? Everything? Or maybe a few key elements?
- What are the different variations for future mineral use besides just, up and to the right?
- What are the GHG emissions generated by disturbing soil microorganisms (to open mines, to build roads, etc.)?
- What alternative consumption patterns might reduce overall demand for critical minerals?
- What are the other needs that would increase alongside REE production increases.
- What elements would have the most significant environmental, economic, and/or security impacts.
- What are the opportunities for planned obsolescence (of specific tech and logistical infrastructures) and therefore the reduction of demand for certain critical minerals?
- Do we start thinking about which foreign countries are "reliable and responsible partners" in developing a future critical mineral supply chain and which are not?
- Where can we collaborate with China?
- What is the future of global environmental cooperation in issue areas like this one? Is the age of global multilateral agreements/frameworks behind us? Or are these indispensable?
- How do we measure the efficacy of public education campaigns? How to inform publics in the age of digital misinformation?
- What legislation/permitting requirements need to be updated to keep up with future demand?
- Are we producing enough skilled workers to address our current and future needs in the critical materials space and adjacent fields?
- Looking at better integration of programmatic efforts across both the government and industry.

SESSION C: Mineral Recycling & Reprocessing Technologies

Question 1: What are the roadblocks that affect the resilient supply of critical minerals?

- Collection of widely scattered end-of-life wastes.
- Characterization of heterogenous tailing and slag piles.
- Lack of incentive for critical element recycling of e-waste.
- Products are generally not designed to be recycled or their materials recovered.
- Limited economic viability to recover things other than base and precious metals.
- Having steady demand for materials over a 5-7-year period.
- Having predictable policies from local governments and international organizations.
- Perceived truths and perceived falsehoods.
- Domestic mining does not have a good environmental image.
- Uncertainty in the market: This means mining firms hesitate to invest in these minerals.
- Public perception of the processes needed to properly create a diversified supply chain.
- Regulatory environment for mining and processing (smelting) permits.
- Need for integrated/updated industrial policy.
- Disincentives for efficient multi-mineral exploitation from a single site.
- Lack of recycling—an example is smartphones.
- Lack of reuse, reclamation, and recycling places burden for increasing supply almost entirely on opening new mines, which are often controversial.
- Lack of robust collection and aggregation at end of life.
- Limited profit margins for refinement of raw materials for end-uses.
- Lack of market certainty for firms that would otherwise be inclined to invest in social and environmental safeguards.
- In some minerals/metals, we have lost the processing expertise because we have been out of the game for a while.
- Perceived truths and perceived lies—China's role and perceptions—disaggregate China’s government from its people and even different levels of Chinese government.
- How we frame the problem can lead to us focus on the wrong aspects of the problem.
- Lack of diversification. Supply chains should be re-regionalized as a matter of regional coordination (in the Americas for example).
- Either the perception or reality that recycling to get critical commodities is harder/more expensive than new mining.
- PR for increased information of reprocessing technologies.
- Concern over domestic recycling and processing sites. Downsides of NIMBY.

- Regarding overcoming NIMBY mindset—we need more information about the ecological and health impacts of these poorly studied elements.
- There are critical regions for which there are no mining information, so increase research in those areas are necessary.
- Lack of information of content of wastes.
- Reprocessing technologies: poor understanding of the department of critical elements in a wide range of materials.
- We need more smelters in the US to keep critical mineral rich waste piles.
- I think we need to know what minerals host critical elements that could be recovered in consumer products.
- How to pre-process materials in the most efficient way to extract metals, leading to how to break up a phone into its components efficiently.
- Long regulatory and permitting of mining and mineral processing facilities.
- What is the mass balance of critical elements that could be recovered as a by-products from currently operating mines. Can we use that info to identify potential extraction targets?
- If the question were targeting domestic supplies, I think we can't do anything without getting buy-in for the public. As long as the general public believes mining and smelting is dirty, it's going to be a very tough road to open a domestic smelter, even if it is for recycling.
- Public perceptions.
- Geopolitics.
- NIMBY.
- US deindustrialization…Excellent talk on “where are the smelters?”.
- For recycling, lack of efficient collection systems.
- For recycling, end-of-life products, lack of efficient collection systems.
- For recycling both process wastes and end-of-life products, the challenge of recovering multiple materials.
- Lack of understand of where raw materials come from.
- Lack of recycling opportunities or awareness.
- Getting funding for and (mines, drilling, sampling) started; permitting.
- Lack of support from the government and the people— (lack of understanding of where the minerals come from).
- Market timing—prices and demand 10 plus years out?
- Cost competitiveness.
- Lack of incentives.
- For recycling end-of-life products, the technical complexity of components and products (e.g. in and rare earths in smart phones).
- Separation technologies that reduce environmental impact, minimize capital costs by reducing footprints, and achieve higher concentrates with fewer steps.

- Water in the Western US, where major orebodies are located, will face increasing demands for water from various stakeholders. Dry, or water-reduced processing, will most likely be required into the future.
- Better understanding of currently available waste streams such as tailings, coal ash impoundments, and e-waste and other recycling opportunities.
- Policy awareness and government support for new technologies/funding.
- Increasing public awareness and recycling facilities for e-waste.
- Public opinion of mining and lack of community support.
- Policy limitation, which causes a delay in granting mining permit.
- Vague and outdated regulations as mining technology advances.
- Limited mineral processing permit.
- Negative public perception.
- Mature, energy efficient processing and recycling technology.
- Cited as roadblocks by the mining and processing industry, but these laws are there to protect the environment. US laws have resulted in 'outsourcing' many activities important to the supply chain for critical mineral.
- Lack of knowledge of the deportment and processing behavior of the critical metals within orebodies.
- Pricing of the commodities and their manipulation.
- Lack of knowledge of critical mineral resources and reserves and materials flow.
- Good examples of "clean, modern" mines/smelters.
- Lack of people to execute research/development/production.
- State/city level policy, regulations, and permitting.
- Lack of content for general public to understand the importance and advocate.

Question 2: What are the most pressing research needs?

- To improve the knowledge of environmental impacts of tailing reprocessing.
- Can we capture critical minerals by recovering pyrite?
- Replacement of carbon as a reducing agent for metal oxides.
- Tracing material flows through products and identify total material concentrations in final products, e.g., nutrition facts for labelling elements/materials.
- Developing methods for quantification and removal of critical elements from production waste.
- Quantifying how much might be available where and in what form. And what it would take to collect and recycle them.
- Methods to quantify presence of valuable metals present in heterogenous materials.
- Automated methods for sorting waste streams.
- Processes that can handle extremely complex feeds (e-waste) while still capturing critical minerals.
- New business models to incentivize recycling and product take-back.

- Metallization and refining.
- Funding for consortia that work together to make co-production economics.
- Economically viable processing of coal waste and mine water for critical minerals.
- How to scale up or deploy research (such as those at universities and critical minerals?).
- Techniques to economically extract as much critical minerals as possible from existing supply chains (co- and by-products)—better understanding of deportment of critical minerals in current supply chains.
- Efficacy of due diligence, social license to operate, labor protections, and other informed consent protocols in protecting local communities and thereby reducing likelihood of future disruptions.
- As we advance technologies that reduce critical minerals, like Co in batteries, the value from recycling decreases.
- Recycling of complex alloy to cut down on the downgrading of recycled alloy.
- Design for reuse/remanufacturing/recycling (Re-X).
- New materials to replace critical minerals.
- Field based research at local mining sites to understand social dynamics that help or hinder productions.
- Specificity of adsorbents in SX and IX.
- Bottlenecks to more widespread reuse, recycling and reclamation.
- Federal, state, county, and municipal policy gaps for implementing a nation-wide recycling system.
- Innovative public policy that addresses these challenges.
- Decarbonization and process intensification.
- Making mining and processing more environmentally friendly (sustainable mining practices).
- Dealing with hazardous byproducts or wastes.
- Demonstration to de-risk and prove out technologies—both cost-competitiveness and full life-cycle considerations.
- Funding for moving technology up the TRL scale to de-risk deployment.
- More systematic and interdisciplinary research for collaboration that leads to easier access to the technologies.
- Research showing the relative environmental impact from domestic recycling and processing.
- Financial cost-benefit analysis of recycling critical commodities, like from used cell phones, to demonstrate feasibility and profitability.
- More relationship between mining companies and universities to improve the research in new technologies.
- If we are thinking about reprocessing mine wastes—need to understand which wastes are likely to contain elements of interest (need knowledge of their partitioning during milling/processing).

- Also need to understand how elements may be redistributed during weathering of mine wastes.
- Identify the metal contents of existing stockpiles and existing production streams, like Te in copper production.
- Metal separation techniques for complex mixtures.
- Socially accepted business models for the efficient separation of electronics from the waste stream.
- Development of environmentally acceptable chemicals/solvents for metal extraction.
- I guess most critical elements are used as metals in consumer products. How are those typically recovered? Do we have the metallurgy figured out on that?
- What are the cutoff grades to make it worth recovering different elements in a consumer product? I'd say go after the lower hanging fruit and get some early wins to build buy.
- Assessment of benefits vs environmental concerns, for example improved metal recovery versus CO2 release during burring of materials.
- Efficient recycling technology.
- Research on how to communicate to the public and the government to bring understanding about mining and processing of materials.
- Efficient separation of rare earth elements.
- For rare earths, better separations and conversion to metals and alloys.
- Commodity tracking.
- Resource minimization in products.
- Substitution elements or materials.
- Reduced energy inputs in processing.
- How to process and recycle materials in an environmentally friendly and safe way (reduce output affecting ozone).
- Improving solvent extraction methods and kinetic or developing alternatives to solvent extraction.
- Detailed assessment of old mine tailings.
- Developing data driven or AI based process optimization. So we need advanced measurement and sensing techniques to build accurate predictive models.
- Alternative materials from more abundant and domestic source.
- Environmental conflict resolution about the role of mining in modern society.
- Understanding of geochemistry of critical minerals.
- Geological mapping and characterization.
- Critical mineral recovery/recycling technologies.
- Economical and green separation technologies.
- Behavioral and logistical challenges to waste recovery.
- New Regulatory framework focused on EPA laws to re-access/reevaluate tailings, dumps and abandoned mines for critical minerals.
- How to get the public as a whole to start recycling e-waste.

- We need to increase the willingness of industry to utilize secondary products.
- Educate Americans on how to recycle—increase collection and its efficiency across North America.
- Understanding what we have in waste materials and how to extract metals from them by recycling and reprocessing.
- Find ways to reduce down-cycling and increase quality of secondary products.
- Where are current recyclers? What do they recycle? What waste streams do they produce?
- Innovative processing technologies/optimization, environmental implication of reprocessing and recycling.

Question 3: What opportunities can lead to the fastest and biggest impact?

- Developing end-of-life recycling technologies.
- Ban the export of scrap/wastes from the US similar to the EU which will force the development of recycling within the country.
- The implementation of tax policies beneficial for the recycling industry.
- Enforcing producer take-back or extended producer responsibility.
- Resurrecting the DLA purchase program for critical materials produced domestically.
- Develop indium recovery method from ITO displays.
- Can vehicle junk yards be a large source of recycled elements? Especially when parts are no longer being salvaged from the vehicles.
- Government subsidies of at least the most critical materials.
- Industry input and partnerships.
- Provide tax incentives for investments in social and environmental safeguards.
- Addressing the public policy gaps.
- Outreach and partnership with communities.
- Providing purchasing guarantees for producers in the Americas to create a baseline of market certainty for their first years of production.
- Mandate redesign standards that increase modularity and facilitate recycling.
- Invest in mine remediation.
- Long term offtake agreements.
- Techno-economic analysis and life cycle assessment to inform technology development.
- ML/AI to accelerate and inform experimental design.
- Extracting critical minerals from tailings etc. at legacy sites.
- Extracting critical minerals from existing production streams (co-product/by-product).
- Better extraction technologies.
- Incentivizing consumers to recycle in a centralized way.

- A proof-of-concept pilot study of recycling or reprocessing for a highly dependent critical commodity, like tantalum.
- Understanding how reprocessing can help offset costs of environmental remediation.
- Changes and better lead times for permitting or processing and recycling plants.
- Mandate requirements that make products necessarily more recyclable for critical elements.
- Easier to mandate that companies return products at end-of-life for recycling than it is to mandate that individuals return products for recycling.
- More efficient environmental politics.
- Government incentives.
- Extended manufacturer responsibility legislation.
- Carrot or the stick. Incentives and fines.
- Public incentives for recycling.
- What if the US gov said we aren't going to export e-waste. And that we will build a recycling facility.
- Some kind of governmental policy that sets a trajectory and we will have to figure out how to get there.
- And sticking with it.
- In many locations, it is really inconvenient to recycle e-waste. Show up at this one little industrial place on the third Thursday at 11am. Let's make it convenient.
- Development of a business model that rewards consumers for sorting of e-waste connected with an efficient reprocessing system.
- Make e-waste recycling convenient!
- Improve knowledge about backyard burning! Number one source of PCB's, volatile toxic elements, etc.
- Change the public perception of recycling means make it easier. Have drop-off sites for e-waste, etc.
- Improve recycling education, for example to issues related to backyard burning.
- Make proper disposal of waste easy.
- Do something big and splashy with rare-earths.
- A US JOGMEC-like entity.
- Awareness campaigns on the importance of minerals, where they come from, how they are used.
- Restart of national stockpiling.
- Private-public co-funding for scale-up evaluations of innovations that are encouraging at lab scale but unproven at commercial scale.
- Increase understanding and awareness to the public—provide education.
- Incentives to process critical minerals in the US rather than exporting materials to be processed elsewhere (i.e. China).
- Understanding of labor and environmental issues associated with mining and processing in some countries/regions.

- Helping under-developed mining countries up-to-date with SAFE mining technologies.
- Reducing the time necessary to complete environmental and mine permitting.
- Positive public perception of mining campaign.
- Increased government funding for metallurgy and recycling R&D.
- Government intervention to induce recovery of critical minerals.
- More funding should be given to mining and mineral education.
- The USA should make more investment in developing African countries.
- Mining workforce development.
- Recycling.
- Creation of a system or systems for effective e-waste collection and recycling.
- Create incentives for recycling—both at the collection level and secondary product level.
- Electronic recycling bins alongside plastic and wood bins. Media campaign, social media, TikTok, Snapchat, etc.
- Engagement of industry in recycling.
- Public education and reworking regulations/policies to create a new recycling system.
- Our infrastructure needs to follow the mantra of Recovery, Reuse, Re-manufacture, and Recycle.

Question 4: What skills training is required to meet future workforce demands?

- Systems perspective, life cycle thinking.
- Interdisciplinary teams.
- Aside from engineering fundamentals, new graduates need the ability to conduct technical/economic analyses of new and existing production methods.
- Materials handling, chemical processing, machine design, finance, environmental (including LCA), metallurgy, resource characterization.
- Folks with multi-disciplinary skills—engineers and scientists who are able to engage the community and stakeholders, social scientists who understand technology, etc.
- Graduates with the ability to handle large datasets regardless of their domain expertise.
- Complex problem solving—mining is a highly technical expertise that must unavoidably take place in the context of real-world complexities.
- Multi-disciplinary approaches are needed—this may be a BS with at least a minor or dual BS or BS plus MS plus PhD, all in different fields.
- Broadening of multi-field competency of the workforce.
- Encourage and cultivate multidisciplinary teamwork.
- More field-based experience in a variety of settings: extractive (large-scale mine, small-scale mine, artisanal operation).
- Business management or economics.

- Life cycle thinking.
- We will need people who can develop new processing methods for extracting critical elements from finished products (cell phones) and re-processing (sludge and tailings).
- Combined knowledge of geochemistry/geology and mineral processing/metallurgy.
- Fill the gap of economic geology to mineral processing.
- Thermodynamics—people who can determine basic partitioning parameters (helpful throughout ore formation, processing including recycling, environmental mobility).
- Sustainability, environmental impact and LCA training for students coming into the mining, metallurgy, and reprocessing industries.
- Machine learning plus AI married to robotics.
- We need folks who can communicate to deliver science knowledge (i.e. backyard burning number one source of PCBs) to the public.
- Science for Dummies Manual for Politicians.
- I'd extend that to be cross training between a couple of related disciplines. Mining-mining engineer-metallurgy-etc.
- Students need to learn more about communication to a target audience. And some about finance/economics.
- Education at the nexus of geology and engineering.
- Identify and help students understand pathways towards degrees at the nexus between science and engineering.
- Leadership—communication, social, teaming.
- Understanding and application of programming—especially with AI and Big Data.
- When a mine closes down, teach/train workers that they are still needed to help—especially when it can reopen.
- Know how to do things safely.
- Depth in a specific area (EE, CEE, etc.) along with good complementary skills (operations management, economics, etc.).
- How to recruit.
- Good STEM education.
- STEM in general, but it has to be more focused on applications. Chemistry, Mineralogy, Crystallography, etc.
- Science education has to start young! Science and math. It's cultural.
- Pay your teachers more.
- Professional continuing education for working professionals.
- Communication skills (e.g. public and policymakers).
- Circular economy.
- Ability to work with a diverse base of stakeholders.
- Data analytics and data literacy.
- Mineral economics.

- International relations.
- Conflict resolution skills.
- Programming (Python).
- Statistics.
- Basic understanding of environmental law and mining regulations.
- Skills in environmental justice: Indigenous land rights.
- Understanding of life-cycle assessments.
- It is a zero-sum game, need to ask the parallel question of what current skills training will go away? Maybe the solution is to produce more M.S. level and above graduates to get ALL the skills they need (both new and existing).
- A novel approach of mineral processing and recycling of waste including tailings dam and abandon mines.
- Training students on important skills.
- Training students on communication and presentation skills.
- UA closed its minerals engineering program in the early 1990s. In terms of exploration, basic geology training is critical (structural, geology, mineralogy, petrology, geochemistry.
- Promoting thesis graduate programs to encourage problem solving skills of students
- Professional development skills.
- We need more venues (conference, workshops, journals, internships) for exchange of information.
- Interdisciplinary skills across the board.
- Understanding of what the critical minerals are and how they are used.

Question 5: What other questions should be asked, but are commonly overlooked?

- What is the risk of critical minerals becoming "ordinary" or obsolete?
- Specifically, what new technology can be employed to re-process old wastes?
- How do we start the conversation with policymakers?
- What is the resource endowment above-ground?
- Why is recycling not already done more?
- Who stands to benefit and who stands to lose?
- Life cycle thinking, systems approach.
- Artisanal and small-scale mining.
- What can be learned from long-term success stories.
- Possible decommodification of critical resources.
- How can we get private industry to be more proactive in this issue? Some price regulation? Incentives?
- Should we create more incentive to make longer-lasting products.
- Design products to last longer.

- Prioritize elements/commodities that can be readily recycled.
- What products can't or shouldn't be recycled? Should there be a stick/carrot approach to reduce production of these products.
- Increase bonds for remediation!
- How do we create a workforce to begin with?
- What kinds of incentives could move the needle on byproduct production or recycling?
- What would it take to change the negative perception of mining? Want an iPhone? Become a miner.
- How to improve the negative perception of mining/mineral processes for the next generation.
- How to reduce the environmental impact of mining, e.g. water usage and energy usage.
- Can (or how can) public-private partnerships be successful?
- Not necessary ignored, but we haven't discussed. Reprocessing of tailings or other waste.
- Where should the public be disposing of appliances for recycling (refrigerators, washing machines, dryers, cell phones, etc.).
- Why do some recycling centers request payment to recycle materials/appliances?
- Why does the government not provide incentives for recycling more? Or processing critical materials.
- What is the government's role in the developing and subsidizing critical material mines and refineries?
- What current skills training will go away?
- How can we build a sustainable policy for mineral development that overcomes the election cycle?
- What is the role of natural history museums and local non-profits in increasing awareness of mining and engaging in public outreach?
- Should agriculture and mining be paired together?
- The efficacy of the academic-industry collaboration.
- Does the mining academics get enough funding for mining and mining related research?
- Summer workshops or field camps for students of mining, geology, and mineral engineering.
- Are landfills a place we can look for reprocessing materials?
- What long term approaches can be developed to make this topical area move forward?
- I think social media might be overlooked as a tool to get people to recycle.
- What will be different this time for recovery, recycling, etc.?+

SESSION D: Technological Alternatives to Critical Minerals

Question 1: What are the roadblocks that affect the resilient supply of critical minerals?

- Economics.
- Specific to magnets—critical material-based magnets (such as Neodymium) are simply superior (especially at manufacturing scale) to alternatives.
- Technological R&D isn't driven much by supply issues.
- Insufficient funding in R&D.
- Lack of robust supply data.
- Unavailability of data.
- Intermediate.
- Data may exist but corporate actors do not provide access.
- Identify diversity of sources.
- Efficient extraction methods for tailing or coproduction methods that add value for primary production.
- Reduced energy and carbon footprints for US operations.
- Time required to obtain mining licenses to operate.
- The absence of resource diplomacy.

Question 2: What are the most pressing research needs?

- Supply-based research.
- Extraction to make minerals non-critical.
- Research into a variety of alternative technologies to reduce over-dependence of particular minerals.
- Many technically feasible resources, determining economically feasible lacking.
- Quantification of potential critical element resources as well as the potential for recovery.
- By-product or co-product data is often unavailable but would be useful—estimates are possible.
- Program development to increase the accuracy of geologic models.
- Research in recycling, collection and dismantling of products. Keep critical materials in the economic system as much as possible.
- Good public policy.
- Research needed on forms of state support to critical mineral industries—this support is widespread in China.
- Explain how and why minerals are essential to everyday life; increase public awareness of how many products depend on mining and critical minerals; highlight strategic value.
- Stakeholders—developing effective community relations and stakeholder engagement with e.g. indigenous peoples, local communities. Expand these practices beyond Canada and like-minded societies.

- Industry/research establishment. Study EU integration as a process of creating stable transnational supply chains to link former belligerents. Consider resources in South Africa and other societies undergoing transitions to more.

Question 3: What opportunities can lead to the fastest and biggest impact?

- Breakthroughs, but are known unknowns.
- Mine waste processing/reprocessing.
- Efficient recycling methods.
- Orphan mine liability.
- More effective recycling, through companies being able to control the life cycle of their products' recyclable components.
- Debatable if considered opportunity, but: More cooperation between governments to stabilize regions and relationships to reduce criticality.
- Quantify and adapt existing know-how and infrastructures to accelerate the transitions.
- Global governance on strategic minerals.
- Mines in Central Europe and Germany that are closing, how will this land be used again, how can existing infrastructures help in this process and foster transition toward clean energy in other ways, e.g.
- Global needs to priorities—explore opportunities for international cooperation, rather than competition. Examine the EU as an example of effective transnational governance that started with coal and steel supply chain.

Question 4: What skills training is required to meet future workforce demands?

- Train developers in sustainability/LCA.
- Demand for graduates lacking.
- Systems thinking, modelling large and multiple scenarios for decision-making (incl finance/mineral economy and public acceptance).
- Interdisciplinary knowledge in each discipline.
- Multidisciplinary and the ability to interact with different stakeholders (academia, industry, and governments).
- Life cycle assessment and thinking.
- Communication and collaboration between government and industry.
- We should no longer distinguish so radically social sciences and natural sciences!
- Equip researchers to participate in collaborations bridging distant disciplines, across the boundary between the natural and social sciences.
- Incorporate consideration of responsibility, social impacts into training for students in highly specialized technical fields focused on resource exploitation.
- Greater emphasis on critical thinking in undergraduate programs.
- Historical aspects of mining and economic consequences.

Question 5: What other questions should be asked, but are commonly overlooked?

- Are they really critical, or just my pet?
- Are there alternatives to these minerals?
- Alternative products are pushed by “best”, but is “best” the enemy of better but more sustainable?
- Tragedy of the commons: could life-cycle costs (and externalities) be part of the process considerations? Should companies look at economic models of impacts?
- How do we make the benefits of securing critical material supply (jobs, goods, renewable energy solutions) accessible to everyone?
- What can we do with what we already have?
- Inertia of different generational attitude.
- Can we continue our high standard of living while talking about ecology?
- Are we not partly victims of our own contradictions?
- Population growth (9 billion people) require us to fundamentally rethink resources needs and consumption patterns anyway? How robust are our predicted demand curves to changes major changes and forthcoming?
- Can we rethink basic assumptions and attitudes toward consumption of resources? In various areas of life, e.g., housing, transportation, etc.
- Consumer perspective. What do we need today? What are our actual "needs"? Can we radically transform consumption patterns? E.g., do we really need to drive such long distances, demanding such.

Appendix C: Workshop Organizing Committee

- Dr. Marek Locmelis (Workshop Chair), Assistant Professor, Department of Geosciences and Geological and Petroleum Engineering / Thomas J. O'Keefe Institute for Sustainable Supply of Strategic Minerals, Missouri University of Science & Technology.
- Dr. Angela Lueking (Workshop Committee), Vice Chancellor for Research and Dean of the Graduate School, Montana Technological University.
- Dr. Michael Moats (Workshop Committee), Professor and Interim Department Chair, Department of Materials Science and Engineering / Thomas J. O'Keefe Institute for Sustainable Supply of Strategic Minerals, Missouri University of Science & Technology.
- Dr. Kwame Awuah-Offei (Workshop Committee), Professor and Interim Department Chair, Department of Mining and Nuclear Engineering / Thomas J. O'Keefe Institute for Sustainable Supply of Strategic Minerals, Missouri University of Science & Technology.
- Dr. Lana Alagha, Associate Professor (Workshop Committee), Department of Mining and Nuclear Engineering / Thomas J. O'Keefe Institute for Sustainable Supply of Strategic Minerals, Missouri University of Science & Technology.
- Dr. Mark Fitch (Workshop Committee), Associate Professor, Department of Civil, Architectural and Environmental Engineering / Thomas J. O'Keefe Institute for Sustainable Supply of Strategic Minerals, Missouri University of Science & Technology.
- Dr. Alanna Krolikowski (Workshop Committee), Assistant Professor, Department of History and Political Science / Thomas J. O'Keefe Institute for Sustainable Supply of Strategic Minerals, Missouri University of Science & Technology.
- Melanie Keeney (Public Relations), Director of Engagement and Outreach, Marketing and Communications, Missouri University of Science & Technology.
- Jackie Sansone (Administrative Support), College of Engineering and Computing, Missouri University of Science & Technology.
- Tammy Mace (Administrative Support), College of Engineering and Computing, Missouri University of Science & Technology.
- Evette Eickelmann (Administrative Support), Energetic Materials, Rock Characterization, and Geomechanics Research Center, Missouri University of Science & Technology.
- Shelby Clark (Administrative Assistant), Department of Geosciences and Geological and Petroleum Engineering, Missouri University of Science & Technology.