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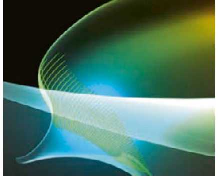

PERSPECTIVE

Materials scarcity during the clean energy transition: Myths, challenges, and opportunities

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ABSTRACT

In this commentary, we examine the myth of materials scarcity, explain the compelling need for innovation in materials in helping supply chains dynamically adapt over time, and show how the materials research community can effectively engage with industry, policymakers, and funding agencies to drive the needed innovation in critical areas.

Efforts to reach net zero targets by the second half of the century will have profound materials supply implications. The anticipated scale and speed of the energy transition in both transportation and energy storage raises the question of whether we risk running out of the essential critical materials needed to enable this transition. Early projections suggest that disruptions are likely to occur in the short term for select critical materials, but at the same time these shortages provide a powerful incentive for the market to respond in a variety of ways before supply-level stress becomes dire. In April 2023, the MRS *Focus on Sustainability subcommittee* sponsored a panel discussion on the role of innovation in materials science and engineering in supporting supply chains for clean energy technologies. Drawing on examples from the panel discussion, this perspective examines the myth of materials scarcity, explains the compelling need for innovation in materials in helping supply chains dynamically adapt over time, and illustrates how the Materials Research Society is facilitating engagement with industry to support materials innovation, now and in the future.

Keywords corporate/business · critical materials · outreach · society · sustainability

Discussion

- Demand for certain materials used in clean energy technologies is forecasted to increase by multiples of current production over the next decades. This has drawn attention to supply chain risks and has created a myth that we will “run out” out of certain materials during the energy transition. The reality is that markets have multiple mechanisms to adapt over the long-term, and near-term shortages or expectations of shortages provide a powerful incentive for action. In this commentary, we highlight different ways materials innovation can help solve these issues in the near term and long term, and how the materials research community can effectively engage with industry and policymakers.

The Spring 2023 panel discussion “Materials Needs for Energy Sustainability by 2050: Are we really at risk of running out of critical materials?” was held in San Francisco, CA on April 10, 2023 and was attended by over 100 people.

Introduction

Multiple market drivers are accelerating efforts to reach net zero targets by 2050. Foremost, this includes global regulatory shifts including Europe's *Fit for 55* program, the United States' *Inflation Reduction Act* and *Infrastructure Investment and Jobs Act*, and India's *Faster Adoption and Manufacture of Hybrid and Electric Vehicles Scheme*. In addition, deployment of battery energy storage systems, predominantly for grid-scale storage, is expected to increase at an estimated 30% compound annual growth rate over at least the next decade.[1]

This rapid and dramatic shift in the energy landscape has profound materials supply implications; the energy sector will soon emerge as a major force in the mineral market, a stark contrast from historical experience. For example, the use of lithium in electric vehicles is expected to grow by over an order of magnitude by 2030, with the additional demand corresponding to multiples of current global production.[2] Similar projections of significant demand growth exist for rare earth elements (REE), nickel, cobalt, copper, and other materials used in clean energy technologies.

Materials supply risk is not new, and industry has been dealing with similar challenges for a long time.[3] However, the magnitude and breadth of anticipated changes across supply chains, driven by the scale and speed of the energy transition and constraints imposed by environmental and social concerns, raises an important question about our ability to reach decarbonization goals. Simply put, are we at risk of running out of critical materials during the energy transition?

On April 10, 2023, the MRS Focus on Sustainability subcommittee hosted a panel discussion exploring this question as part of its on-going series on *Materials Needs for Sustainability by 2050*. This issue was examined from both the demand side, focusing on new applications and development of corresponding supply chains, and the supply side, considering new sources of supply including circularity approaches at end of product life. Panel members shared examples drawn from their experience in industry and at national laboratories. Two overarching these were the role of innovation in materials development and processing and the need for effective cooperation across industry, government, and academia.

This commentary elaborates on topics from the discussion, with the intent of furthering MRS engagement in this area. The first part explores why the idea of "running of out materials" may be a myth, due to the ability of markets to adapt over the long term, and the powerful incentives for action created by near-term shortages or expectations of shortages. The second part highlights aspects of commercial response to supply challenges that the materials research community should appreciate. The final section provides illustrative examples of how materials innovation can help supply chains dynamically adapt over time.

Why the idea of "running out" is a myth

Critical materials are designated as such because they have a combination of vulnerability to supply disruption, and significant impacts from disruption. However, there are important nuances since criticality depends on who is asking the question. For the energy transition, electrification is expected to play a leading role and the rapid adoption of batteries, electric motors, and other technologies used in generation and distribution implies an aggressive growth curve in the coming years. Growth in hydrogen and nuclear power is also expected to be substantial. Forecasts for materials demand are obtained by multiplying the material intensities for each application by projected deployment over time. In this way, expectations for rapid growth translate directly into concerns that demand will exceed supply.

Supply and demand mismatches, particularly in rapidly evolving industries, are not uncommon. Short-term disruptions can, and will, also happen because of production shutdowns due to social or political unrest, and geopolitical interventions. However, markets are not static and shortages and expectations of shortages provide powerful incentives for industry to evolve, and for analysts to change forecasting assumptions.

Ultimately, materials selection is a commercial decision. Higher costs stimulate innovation and investment. In addition, there are always alternatives, whether direct substitutes or different system solutions. If a material is in shortage, costs go up and alternatives become more attractive. Early recognition of future demand mismatches allows the full suite of options to be considered. This includes research and development of alternative material sets, the development of new supply chain infrastructure including mines and processing facilities, exploration of alternate system solutions or non-traditional material sources, end-of-life recovery, and other circularity approaches. Governments also intervene in response to materials crises.

There are already examples of innovation in each of these areas. Concerns around Co and Ni supply for lithium-ion battery cathodes have prompted research into end-of-life material recovery and alternate chemistries using more abundant materials (*e.g.*, lithium iron phosphate, LFP, or sodium-ion batteries).[4-6] Materials intensity changes from technology innovation can also lead to inflection points in demand. An example of this is the significantly lower materials intensity for REE in phosphors for light-emitting diodes relative to fluorescent lighting.[7] Incentives offered in the US and Europe to reshore or "friend-shore" battery and REE supply chains are another example of near- to mid-term adjustments that reduce longer-term risks of "running out."

Three considerations for materials innovation for critical materials challenges

Given the role of innovation in materials science and engineering in responding to supply challenges, it is important for the materials research community to appreciate three aspects of how supply chains can evolve.

First, different types of substitution can impact supply chains. It is natural for materials research to focus on direct material substitutes, but there are also opportunities for component and system-level replacement, as well as for new manufacturing processes that increase material efficiency. For example, stress on

Co and Ni supply chains can be relieved through development of component and system-level alternatives such as sodium batteries, hydrogen fuel cells, and non-electrical forms of stationary energy storage.[8] Similarly, alternate permanent magnet formulations for use in generators (*e.g.*, substitution of Tb for Dy, or Dy-free nanograin magnets to improve high temperature coercivity) are complementary to efforts to design new machines with RE permanent magnet-free architectures. Another example of alternative manufacturing is the use of additive manufacturing to produce magnets; traditional production of NdFeB magnets can generate large quantities of manufacturing scrap (swarf). New manufacturing methods can result in less waste.[9,10] Commercial entities are open to multiple types of substitution and generally factor in economics, execution risk, and the competitive landscape in choosing which approaches to deploy in different situations.

Second, timing matters.[11] Different parts of the supply chain respond at different rates, so it is important to synchronize innovation efforts to these dynamics. For example, it may take decades from the discovery of a promising geological deposit to actual mine production. Conversely, commercial adoption of substitute materials and components in sectors with fast product cycles (e.g., consumer electronics) can occur in under a year. Since research takes time, awareness of trends in demand helps ensure R&D efforts remain relevant. Market adjustments are not always synchronized, and "bullwhip" effects wherein new supplies emerge as demand recedes can lead to pricing volatility. These issues can be particularly pronounced in critical materials markets as they are often smaller and less liquid.

Finally, broader considerations related to environmental and sociopolitical impacts (*e.g.*, life cycle energy, water, and carbon intensities) can also create opportunities for innovation. New extraction and processing technologies could not only improve efficiency, but also ease or more equitably distribute the environmental burdens of critical material supply chains. Questions of environmental justice extend beyond national boundaries and there is growing interest among resource-rich nations (*e.g.*, Democratic Republic of Congo with Co, Chile with Li, Indonesia with Ni) in securing benefits for their local communities. This landscape means workforce training and other efforts at innovation capacity building will increasingly need a global perspective.

In all three cases, there are lessons the materials research community can draw on when engaging policymakers and funding agencies on critical material issues. First, a broad view is needed when seeking support for innovation. Care must be taken to advocate not just for "new materials," but new systems enabled by new materials. Second, it is important to set proper expectations on how long it will take materials innovation to reach markets. The gap between lab and commercial success can be large, and it is important to ensure policymakers have an accurate picture of what that might look like in various cases. Finally, the materials community should actively engage beyond technical topics, by also advocating for capacity building.

Illustrative examples of how materials innovation can make a difference

New separations approaches

Separation processes are a long-standing area of opportunity to improve the economics and environmental prospects of critical materials production. Many critical materials are extracted from low concentration resources, often with severe constraints on cost, efficiency, and selectivity. In fact, they are often only recovered as "companion" products during the recovery of major metals, since standalone production is not economically viable.[12,13] For example, 81% of vanadium production is attributed to either secondary or co-production from slag generated from the refinement of titanomagnetite/iron ores during steel production, while cobalt is a by-product of copper and nickel ore processing.[14,15] Increasing critical material supplies through new (unconventional) sources will require the development of new separation processes. Innovation is also needed to improve the environmental performance of existing processes to help maintain the social license for production. Development of such separation processes frequently presents new materials science challenges and opportunities.

One example where materials innovation can play a role is in the improved extraction of lithium from mineral sources. Minerals such as phyllosilicate clays or spodumene are the predominant global source of lithium (52–55%). Conventional lithium extraction from clays relies on a high temperature process involving the addition of gypsum and limestone at temperatures between 900 and 1000 °C, referred to as the limestone-gypsum roast (LGR) process.[16,17] Similarly, Li recovery from spodumene is achieved by roasting at 1100 °C and then baking in acid at 250 °C to produce a leachate with lithium and other alkaline ions as their sulfate salts..[18] The leachate then undergoes a series of chemical precipitation and recrystallization steps to produce a battery-grade Li salt product. The use of kilns accounts for the majority of capital costs and energy used, while leachate processing accounts for 70% of total CO_2 emissions (up to 14 t of CO_2 per t of lithium, more than twice that of steel).[19] Developing alternative extraction and leachate separation methods that reduce energy and environmental impacts as well as address equity concerns represent a grand challenge for the lithium mining industry.[20] Numerous strategies are emerging to improve leachate ion separation for lithium as well as other critical materials. These include the development of ion selective membranes with tailored nanochannel and nanopore sizes, ion selective adsorptive membranes, and selective ion-exchange lithium sorbents.[21,22] Exploration of alternative extraction technologies is also increasing, including electrochemically enhanced leaching and selective crystallization approaches.[23–26]

Another example of materials innovation applied to recovery of critical elements is the use of biological or biologically inspired products to reduce environmental hazards associated with conventional recovery methods.[27] Recently, a number of

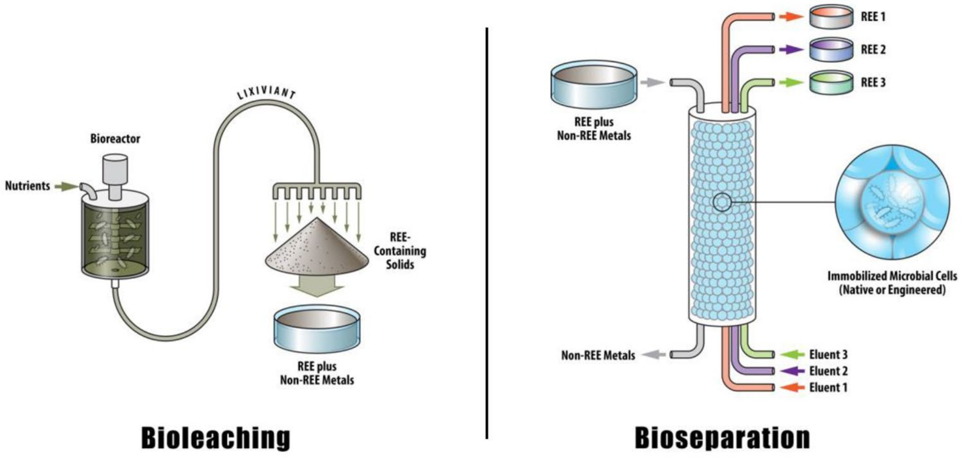


Figure 1. Schematic representation of bioleaching (left) and bioseparation (right). Image from Ref. 27.

researchers have been evaluating the use of microbially produced leaching agents (lixiviants) for the extraction of critical metals from ores, mineral processing wastes, and end-of-life products, using both bacteria and fungi.[28,29] These microbially generated materials can be produced from agricultural or food processing wastes to further improve the environmental footprint and economics of critical material extraction.[30] A final example of a novel class of biomaterials that can be applied to support critical material supply chains are proteins and other biomolecules from microorganisms that rely on lanthanides for their metabolism; because the organisms need the lanthanides, evolution has produced chemical structures with extraordinarily high selectivity and affinity for these elements.[31] The bacterial protein lanmodulin has been immobilized on a porous support medium and demonstrated to enable the facile separation of REE from non-REE metals, as well as separation of heavy from light REE.[32] Engineering of the protein offers ways to tune the selectivity of the separations and provide new materials for application, as does "mining" and discovery of natural variants.[33] The two applications, bioleaching and bioseparation, are depicted in Fig. 1.

Enabling circularity

Circularity approaches such as end-of-life recovery, recycling, and re-use of materials have also attracted significant attention. Research areas where innovation is needed include manufacturing efficiency, reduced materials intensity, and system features that facilitate recovery, sorting, and other aspects of logistics. Some examples are provided below.

Design for disassembly has already entered into commercial practice. Robust interest in the recycling of electric vehicle batteries provides a strong motivation to engineer battery packs to simplify the recovery of high value components at the end of life. Battery packs are assembled with a variety of interface and joining materials to manage thermal performance and ensure hermeticity of the active cells. Figure 2 shows several commercial thermal interface materials and adhesives used in an electric vehicle battery pack. Thermal interface materials assist in the management of battery temperature, which is essential for maintaining vehicle range, extending battery life, and enabling fast charging. Assembly materials must satisfy a host of requirements related to battery assembly and serviceability in the field. DuPont has engineered its BETASEAL 900EI (polyurethane elastomer) class of electrical isolating adhesives to simultaneously bond disparate materials (e.g., coated metals, pretreated thermoplastics, and composites), provide water repellency and dust-tight seals, and act as a secondary barrier in case of leaks from the battery cell.[34] It is a one-component moisture curing system and is soft enough to be de-bonded at a later date. While the adhesive itself may not be recycled, it enables recycling of other high value materials. Continued progress is expected as supporting the circular economy becomes a greater priority for materials science and systems engineering.

Another materials innovation that exemplifies design for circularity as well as a novel approach for encouraging expanded critical material production is the development of aluminum cerium (Al–Ce) alloys and demonstration of their potential to be integrated into existing aluminum recycling operations. Al–Ce alloys are a new class of alloys that contain 6 to 16 weight percent cerium; they were originally developed because the creation of substantial new demand for cerium, the most abundant rare earth, was recognized as a means to improve the economics of production for the whole rare earth series.[35] Creating demand for rare earth elements currently in oversupply creates incentives for expanded production of undersupplied rare earths, while also offering new options for materials designers.

Al–Ce alloys have been found to have outstanding performance for high temperature applications, lower energy costs for production, and excellent castability.[36] In 2020, the Aluminum Association created 3 new designations for Al–Ce alloys. The new standards provide international recognition within the aluminum industry and enable industrial adoption. Extensive prototyping has already been conducted, and parts in commercial production include high-performance pistons and impeller blades.[37] However, because aluminum is so highly recycled due to the energy and cost savings compared to primary production (more than 80% of Al production in the U.S. is from recycling), understanding how the new alloys will impact Al recycling is

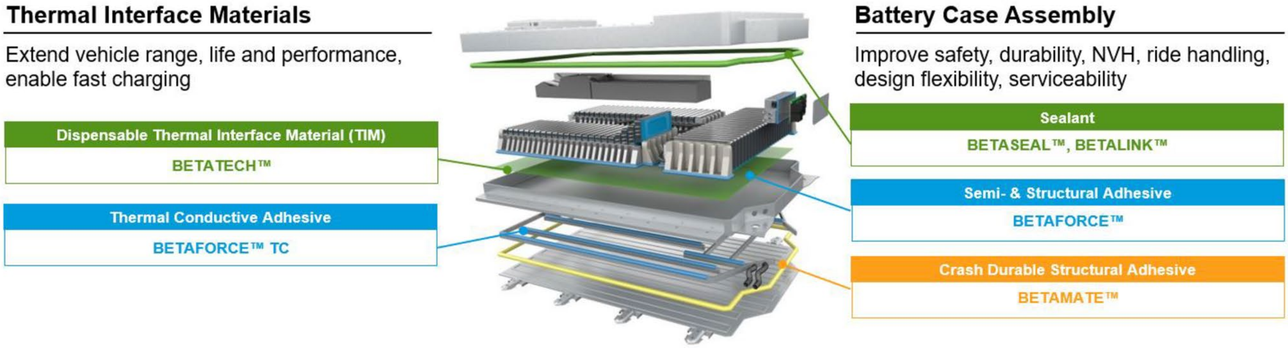
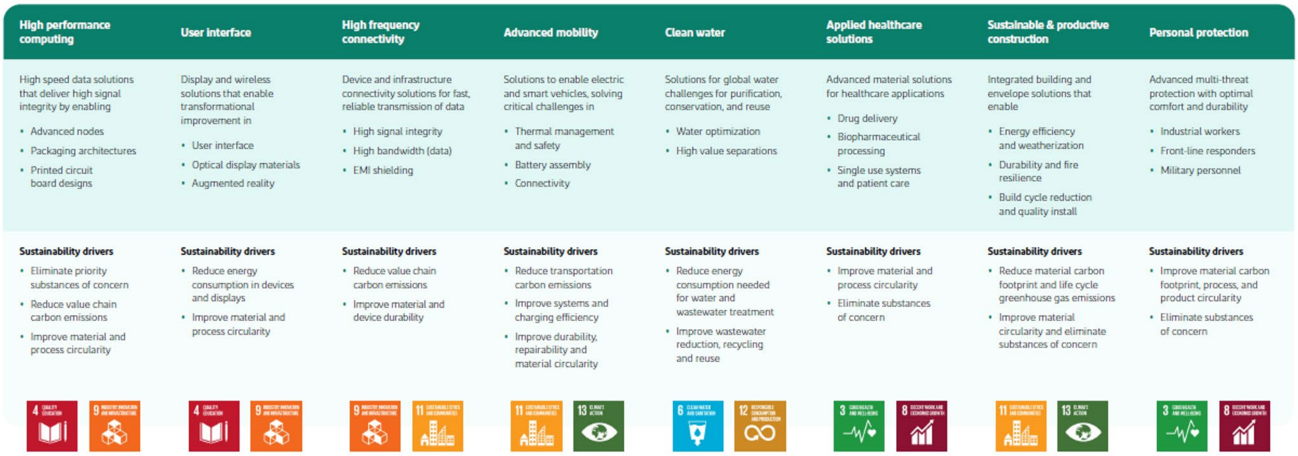


Figure 2. Design for disassembly requires interface and joining materials that are compatible with the recycling process. In addition to meeting multiple requirements related to battery performance and stability, commercial products used in thermal interface and battery case assembly can be designed to be compatible with end-of-life recovery processes. Image from DuPont.



High performance computing	User interface	High frequency connectivity	Advanced mobility	Clean water	Applied healthcare solutions	Sustainable & productive construction	Personal protection
High speed data solutions that deliver high signal integrity by enabling • Advanced nodes • Packaging architectures • Printed circuit board designs	Display and wireless solutions that enable transformational improvement in • User interface • Optical display materials • Augmented reality	Device and infrastructure connectivity solutions for fast, reliable transmission of data • High signal integrity • High bandwidth (data) • EMI shielding	Solutions to enable electric and smart vehicles, solving critical challenges in • Thermal management and safety • Battery assembly • Connectivity	Solutions for global water challenges for purification, conservation, and reuse • Water optimization • High value separations	Advanced material solutions for healthcare applications • Drug delivery • Biopharmaceutical processing • Single use systems and patient care	Integrated building and envelope solutions that enable • Energy efficiency and weatherization • Durability and fire resilience • Build cycle reduction and quality install	Advanced multi-threat protection with optimal comfort and durability • Industrial workers • Front-line responders • Military personnel
Sustainability drivers • Eliminate priority substances of concern • Reduce value chain carbon emissions • Improve material and process circularity	**Sustainability drivers** • Reduce energy consumption in devices and displays • Improve material and process circularity	**Sustainability drivers** • Reduce value chain carbon emissions • Improve material and device durability	**Sustainability drivers** • Reduce transportation carbon emissions • Improve systems and charging efficiency • Improve durability, repairability and material circularity	**Sustainability drivers** • Reduce energy consumption needed for water and wastewater treatment • Improve wastewater reduction, recycling and reuse	**Sustainability drivers** • Improve material and process circularity • Eliminate substances of concern	**Sustainability drivers** • Reduce material carbon footprint and life cycle greenhouse gas emissions • Improve material circularity and eliminate substances of concern	**Sustainability drivers** • Improve material carbon footprint, process, and product circularity • Eliminate substances of concern
4 9	4 9	9 11	11 13	6 12	3 8	11 13	3 8

Figure 3. DuPont's platform approach to materials innovation and sustainability. DuPont organizes its product development efforts around market segments. These are also aligned to various UN Sustainable Development Goals, which allows the company flexibility in its innovation pipeline. Image from Ref. 40.

important to ensure successful commercialization.[38] Results to date indicate that in fact the presence of Ce can be beneficial to secondary Al production, in particular by inhibiting the susceptibility to corrosion typically imparted by the common impurity copper.[39]

Capacity building

Effective materials innovation does not occur in a vacuum. Innovation must also be sustained by a trained workforce and cooperation across industry, research institutions, and policymakers. Moreover, the concerns of communities who may be impacted by new manufacturing or resource extraction facilities must also be considered. Failure to recognize any of these imperatives can create additional barriers to production and exacerbate materials supply challenges.

Industrial actors are increasingly seeking to incorporate sustainability goals into their product value propositions. For example, DuPont has created *Innovation Platforms* aligned with market segments and UN Sustainable Development Goals (Fig. 3). These platforms allow the company to develop bespoke solutions aimed at the specific combinations of requirements from different customers. The innovation pipeline can be adjusted to offer benefits in circularity (*e.g.*, recycled content, packaging, and end-of-life recovery), reduce greenhouse gas emissions during production and use, or be tailored to other priorities indicated by the market. In this way, DuPont is able to maintain nuance and flexibility in its innovation pipeline.

Capacity building also includes workforce development. This includes the development of curricula and training for future employees who will utilize the new materials and implement new manufacturing approaches. There is also a need for constructive engagement across the ecosystem. The breadth of stakeholders means that individual entities may view others as competitors (*e.g.*, universities and national labs competing for research dollars, for profit companies competing for market share). The model implemented by the Critical Materials Innovation (CMI) Hub to encourage collaboration and foster innovation focuses on early-stage technology development and requires all team members to sign a master non-disclosure agreement and intellectual property management plan. In addition, all CMI Hub projects aimed at technology development work with a committed industrial partner, who provides direction as to the most important problems to tackle and whether proposed solutions are feasible for adoption. This model has been highly effective but will be improved going forward by increased emphasis on workforce development and community engagement.

Going forward

The next decade offers tremendous opportunity, and challenge, in scaling up the technologies, commercial ecosystems, and business models that will enable a sustainable energy system by 2050. Materials supply will play a foundational role. There are multiple points of engagement for the materials research community, and innovation efforts and research priorities should be aligned with commercial realities for near-term and long-term impact.

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Authors contributions

AYK: Conceptualization, Project Administration, Supervision, Writing–Original draft, and Writing–Review and editing; EAK: Conceptualization, Funding acquisition, and Writing–Review and editing; YF: Visualization, Writing–Original draft, and Writing–Review and editing; AZH: Visualization, Writing–Original draft, and Writing–Review and editing; RWG: Visualization, Writing–Original draft, and Writing–Review and editing.

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Data availability

No datasets were generated or analyzed during the current study.

Declarations

Conflict of interest

The authors declare no conflicts of interest. The views expressed are those of the authors and do not reflect the official policies or positions of any entities they represent.

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Appendix 1: Panel discussion summary

MRS 2023 Spring Meeting
April 10, 2023
San Francisco, CA
Yoshiko Fujita (Idaho National Lab/Critical Materials Innovation Hub)
Andrew Haddad (Lawrence Berkeley National Laboratory)
Robert Gray IV (Dupont)
Anthony Y Ku (moderator, Xiron Global).

Event description

Efforts to reach net zero targets by the second half of the century will have profound materials supply implications. For example, the use of lithium in electric vehicles is expected to grow by over an order of magnitude by 2030, with the additional demand corresponding to multiples of current global production. Similar projections exist for rare earth elements, nickel, cobalt, and other critical materials used in other clean energy technologies, and accelerate through the next decades.

Materials supply risk is not new, and industry has been dealing with these types of issues for a long time. However, the magnitude and breadth of anticipated changes across supply chains, driven by the scale and speed of the energy transition, raises an important question about our ability to reach decarbonization goals. Simply put, are we risk of running out of raw materials during the energy transition?

This interactive event will bring together participants from industry and the policy world to consider this question. The panel discussion will look at the "big picture" of materials use in clean energy and sustainability, explore how industry and government actually diagnose and respond to supply chain risk, and examine the role of innovation in materials science and engineering in helping solve various aspects of the material supply challenge.

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