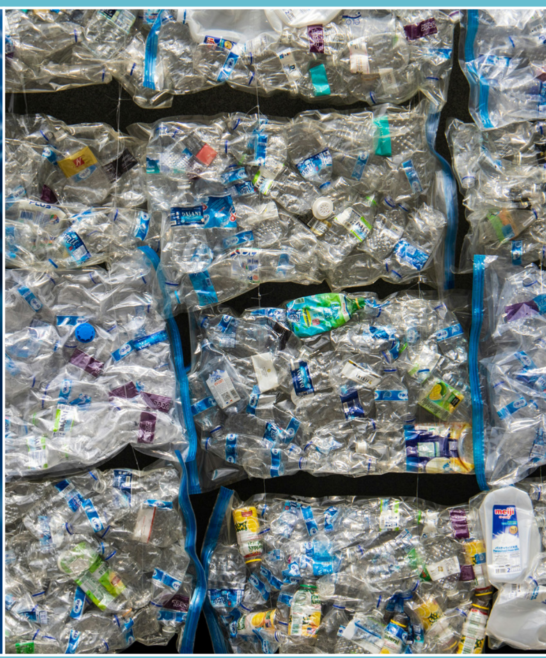
Critical Mineral Recycling & Innovation



May 2025

Table of Contents

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Letters from Leadership

Earthshot Foundation hosted our first dialogues in 2008, declaring – we already know what we need to do – to protect and preserve our natural capital and livable planet. And how to do it – by accelerating the deployment of abundant, accessible, clean and affordable energy for all. A Terranaut® Dialogue begins with a Motive (why) and leads to a Mission (how). **Responsible, nature+ mining** is our motive as we explore the working definition for **true mining** and what it means to **restore trust in mining.** We are delighted to present the 2024 Minologues Series in collaboration with OurEnergyPolicy. The series convenes four cohorts of expert practitioners and stakeholders to discuss intelligent policy design across national security, supply chains, responsible mining and future-mining topics. The series finale will take place on October 7th in Washington, DC. This paper summarizes the consensus contributions from our second cohort. At Earthshot, we believe, "the aim of scientific work [and our work] is truth."

Chase Weir — Founder & Board Chair, the Earthshot Foundation

OurEnergyPolicy's mission is to bring experts together in civil, substantive dialogue to explore solutions to the energy challenges facing the United States. We have partnered with The Earthshot Foundation to explore the crucial questions regarding the availability of critical minerals for American energy needs in this Minologues Series. The Series is a nine-part program, and this paper contains the important insights and recommendations from a working session of leaders on critical mineral supply chains challenges. I want to thank our workshop participants and the staffs at OEP and Earthshot for their work on this document, and — consistent with OEP's non-partisan and open approach to addressing issues— I want to invite all energy stakeholders to read the paper carefully and contribute their views on this vitally important topic.

Bill Squadron — President, OurEnergyPolicy

Executive Summary

This report summarizes the discussion and recommendations of an expert working group on the recycling of critical minerals and innovations in mining and material design. This is the fourth and final working group in the Terranaut Minologues, a series co-produced by OurEnergyPolicy and The Earthshot Foundation to address U.S. concerns over critical mineral accessibility for the energy transition.

Recycling critical minerals and materials is at an economic disadvantage to the production of raw materials produced through mining and processing. While production costs vary greatly depending on the mineral and mine site, raw materials often have lower production costs due to economies of scale and advanced technology. This limitation puts pressure on producers of recycled materials to match those low prices.[1]

While modular manufacturing designs promote supply chain circularity and sustainability, composite designs prioritize optimization and production cost efficiency. Designing manufactured products to be more modular could decrease efficiency, but composite designs have lower recyclability, making it more difficult to achieve a circular supply chain. Due to the higher supply needs connected to modular components, manufacturers are more likely to adopt composite designs to minimize costs.[2]

Many recyclers face inconsistent regulations regarding the management and transportation of Electric Vehicle (EV) batteries due to their hazardous material classification. These inconsistencies slow progress in both recycling ventures and innovation.[3] Refining and modernizing federal and state regulations of critical materials would remove unnecessary barriers to progress while maintaining safety standards.

Extended Producer Responsibility (EPR) is a policy approach that is gaining traction to encourage environmental sustainability, promote recycling, and shift waste management costs from local municipalities to producers.[4] While this policy approach can be beneficial at the state level, a federal EPR could unintentionally disincentivize innovative technology on a large-scale. EPR could also create market imbalances that favor larger producers over smaller producers with limited resources. For these reasons, allowing states the discretion to establish their own EPR policies facilitates a healthy ecosystem for both innovation and circularity improvements.

Automation and Artificial Intelligence (AI) can be integrated into recycling processes to improve efficiency.[5] However, recycling companies may struggle to invest in new technology due to the need to remain competitive in cheap mineral markets. Low mineral prices create thin margins for recyclers to remain competitive with raw mineral producers, therefore limiting their abilities to integrate expensive technologies. Fortunately, alternative technological advancements, such as X-Ray sorting, present more favorable options when weighing the trade-offs between the costs and benefits of integrating innovative technologies.

Innovations in battery chemistries could significantly accelerate electrification efforts and alleviate demand for critical minerals.[6] The commercialization of the solid state battery could improve safety levels of EVs, charge faster, and hold more energy density for longer range. The sodium-ion battery could provide an alternative to the lithium-ion battery that reduces the demand for lithium, a critical mineral with limited production capacity compared to sodium.[7]

Supporters of circular supply chains are exploring ways to reintroduce discarded materials back into mineral and manufacturing supply chains. These efforts continue to gain traction with the development of new technologies that make extracting valuable minerals from landfills and reprocessing waste tailings more economical.

The working group made the following recommendations for U.S. policy:

1. Create More Uniformity in Material Regulations
2. Support State-Level EPR Programs
3. Prioritize Targeted Research Endeavors
4. Include Circularity Considerations in New Battery Designs
5. Participate in International Partnerships for Technology Transfer

Introduction

The Terranaut Minologues brings together experts in the field of National Security,[8] Supply Chains,[9] Responsible Mining, and Recycling and Innovation to explore challenges and opportunities for acquiring enough critical minerals to fuel the energy transition.

The previous working group, Responsible Mining, highlighted that mining is still necessary to meet current demands for critical minerals and materials in the short term, and it addressed how to source critical minerals appropriately through modern mining. This working group will explore how the mineral industry can close the supply chain loop and accelerate its progression towards a circular supply chain through recycling and innovation.

Recovering critical minerals and materials through recycling processes provides an alternative to raw critical minerals produced from the heavily industrial process of mining and processing metal ore. There are many reasons to invest in critical mineral recycling infrastructure. Expanded recycling can assist in fulfilling international demand for critical minerals and improve supply chain circularity. It removes geological barriers to supply chain diversification, and it can aid in the tempering of geopolitical tensions over trade. Expanded recycling would also mitigate pollution and land degradation associated with landfills and resource harvesting.[10]

Incremental innovations involve small, gradual improvements to existing products, services, or processes. In industries that use critical minerals and materials, incremental innovations in technology are often less risky and can lead to significant improvements over time. However, their impacts can be marginal in shorter time periods. Disruptive technological innovations can create new markets and value networks, eventually disrupting and displacing established market leaders and products. While industry leaders and investors may fear disruptive innovations and their potential to completely alter current markets, some disruptive innovations could be the key to overcoming supply bottlenecks and barriers to supply chain circularity.

"Disruptive innovations could be the key to overcoming supply bottlenecks and barriers to supply chain circularity."

The readiness of technological innovation can be assessed in three steps. First is the **Technology Readiness Level** (TRL), which denotes the feasibility of innovative technology to successfully perform its intended purpose. The **Manufacturing Readiness Level** (MRL) refers to the ability to produce innovative technology at scale consistently and with good quality. Lastly, **Integration Readiness Level** (IRL) indicates the ability of a company or governing body to integrate a new innovation into their facilities, rely on the new technology, and produce a final product that maintains the same or better quality as before integration.[11]

Reducing Demand for Raw Critical Minerals

Research and development aimed at reducing demand for raw critical minerals can fall into two major categories. One approach focuses on innovations that will enhance circularity of critical mineral supply chains and expand recycling capabilities. The second approach focuses on innovations that reduce overall demand for critical minerals, ideally creating less demand for both raw and recycled materials. While the former prioritizes circularity, the latter prioritizes performance optimization and cost efficiency of production.[12]

Many in the battery recycling industry are advocating for modular designs of electric vehicle (EV) batteries, which would simplify disassembly for reuse and promote both circularity and sustainability.[13] In addition to improving recyclability, modular designs also make replacing and repairing components easier, thereby extending the use life of the manufactured product.

However, since modular designs can be non-optimal for performance and lead to increased production costs, composite designs are more often utilized in manufacturing. Specifically, composite lithium-ion battery designs facilitated a reduction in EV production costs.

Innovations in Waste Sorting

Artificial Intelligence (AI) and automation could be useful tools to identify and remove valuable materials from landfills. AI can be trained to recognize different chemistries, alloys, or other material properties in waste streams so they can be identified and sorted out for recycling. Automation can improve processing capacity and reduce manual labor requirements.[14] Working group members predicted that incorporation of AI and automation in recycling processes could contribute to incremental cost savings in critical minerals recycling that can make those material sources more economically viable. These technologies diminish the hurdles of labor costs associated with the manual sorting of waste streams. [15]

While AI and automation could improve operational efficiency, especially in times of labor shortages, these technologies also have their own integration costs. Integrating technological innovations such as AI in recycling projects targeting critical minerals and materials can be difficult given the associated cost constraints these ventures face to become and remain economically competitive. Producers of recycled critical minerals face thin margins caused by low mineral prices that even the producers of raw critical minerals through traditional mining are finding difficult to maintain.[16]

AI technology is not the only technological method of automation that could increase material recovery and processing capacity. One technological process that is currently being used by companies like Redwood Materials for battery recycling is X-Ray Fluorescence (XRF) sorting. This recycling method uses XRF machines to penetrate materials and detect differences in density and composition of materials based on how XRF are absorbed or scattered by them.[17] With this automated sorting method, Redwood Materials is able to recover over 95% of critical materials from recycled lithium-ion batteries.[18] This type of sorting is one example of automated sorting technologies that have improved recycling capacity at affordable integration costs.

Innovations in Battery Chemistry

Batteries used for energy storage and electric vehicles (EVs) are a major driver for increased demand for critical minerals.[19] While automated sorting and increased recycling of critical materials can contribute to incremental improvements in mineral availability, innovations in battery chemistry can fundamentally change the existing market.[20]

Two major emerging innovations in battery chemistries are the solid state battery and the sodium-ion battery.[21] The solid state battery is an emerging chemistry that uses a solid electrolyte instead of the liquid or gel electrolytes found in current batteries. This new battery chemistry would have multiple benefits over its predecessors. It has higher thermal stability, can charge faster, is lighter, and has higher energy density. It also has been predicted to have a longer life span and significantly diminished environmental impacts. However, at its current stage of development, it would be more expensive to produce and perform poorly at low temperatures.[22] Regardless, improved safety levels connected to the integration of solid state batteries could lead to wider adoption of EVs, thereby accelerating the energy transition and demand for critical minerals.

The sodium-ion battery is being developed as a potential alternative to the lithium-ion battery.[23] Lithium-ion batteries are currently the most popular choice for EVs and grid energy storage. This common battery chemistry uses lithium compounds for the battery electrolyte. Electrolytes play a key role in batteries by facilitating the flow of ions between the positive and negative electrodes, which is essential for the battery's operation. They have high energy density, long life-spans, and are relatively lightweight. However, they can be expensive and vulnerable to supply chain bottlenecks associated with the key component of lithium, a critical mineral.[24]

Sodium-ion batteries replace the electrolyte made from lithium compounds with sodium-based compounds. This game-changing development, if commercialized, could lead to a market shift to a battery with an abundance of cheaper raw materials for battery feedstock.[25] Replacing lithium-ion batteries at a commercial level with an alternative battery chemistry that reduces reliance on this critical mineral would be a significantly disruptive breakthrough in the battery industry. It would reduce both demand for lithium and the associated pressure to increase lithium production capacity.[26]

Complications in Transporting Recyclable Materials

EV batteries often have to be transported across jurisdictions to be recycled in established facilities. One challenge that often arises in the transportation process is that the materials in EV batteries are often classified as hazardous materials. Due to this classification, transportation of these materials can be more difficult, especially across state and international borders, since regulations on the management and transportation of hazardous materials can be different between jurisdictions.[27]

Navigating the different regulations for transporting and managing hazardous materials across federal, state, and tribal jurisdictions poses a barrier that can slow down or deter recycling initiatives for critical materials. Creating more uniformity in the regulation of hazardous materials destined for recycling facilities could reduce uncertainty. Consistent regulations for the handling of this category of hazardous materials would remove a barrier to investments in recycling infrastructure, lower a hurdle to achieving a more circular supply chain, and ensure that these hazardous materials are safely handled across jurisdictions.

Extended Producer Responsibility

Extended Producer Responsibility (EPR) is a policy approach where producers are made responsible for the entire lifecycle of their products, including in the post-consumer stage. This typically includes involvement in waste management and recycling programs. When EPR is applied to specific products in a jurisdiction, there must be a plan to divert the target products from landfills.[28]

This legislative strategy has seen significant traction at the state level in the United States. Seven states in the U.S. have EPR laws for electronics and other targeted products to divert these waste streams away from landfills.[29] EPR programs in states such as California, Oregon, Washington, Maine, Vermont, New York, and Connecticut are designed to support waste management, environmental sustainability, and pollution reduction. A sample list of products with EPR in each state can be found in **Appendix A**.

While EPR is gaining traction at the state level for waste management, promoting recycling, and shifting the cost burden of waste management from local municipalities to producers, it also has its drawbacks. If not carefully designed, EPR programs could limit incentives for innovations in product design or recycling processes. For example, if a manufacturer wanted to introduce a novel EV battery chemistry to a market with EPR for all EV batteries, it would need to ensure there is a supporting supply chain infrastructure for its end-of-use management.[30] EPR also creates additional administrative and compliance costs for producers to track, collect, and ensure the proper disposal or recycling of their products.[31] These additional costs would be particularly challenging for smaller producers with limited resources. Therefore, state and local municipalities should keep these potential imbalances in mind when designing EPR programs.

Even with the potential additional costs, EPR programs promote supply chain circularity and waste reduction. They should continue to be implemented at the state level where local officials can determine whether the economic and political conditions are suitable for an EPR framework.

Economic Signals for Innovation and Recycling

The potential benefits of innovative technology can be remarkable, but their impact commercially can be delayed due to a lack of incentive for implementation. Similarly, recycling projects targeting critical minerals and materials have to compete economically with raw material production in both price effectiveness and scalability.[32]

While the working group agreed that stronger economic signals and investments in innovation and recycling were needed, they also worried that too much government intervention may lead to an unsustainable foundation in the long-term. Instead, similar to the earlier recommendation to synthesize regulations on the transportation of hazardous materials across jurisdictions, the working group recommended updating regulations that impact this industry to remove unnecessary barriers to the development of recycling infrastructure and innovation.

Innovations in Waste Processing

Since waste is produced in nearly every step of critical mineral processing and manufacturing, producers and researchers are increasingly interested in finding ways to reutilize these waste elements as feedstock in manufacturing or for other uses. There is also growing interest in treating waste disposal sites as new potential sources of valuable resources. The value of the estimated recoverable metals and minerals in landfills has been appraised upwards of $400 million in the UK alone.[33]

While mining for critical minerals in consumer waste streams may not yet be economical, there are more specific

waste materials that research institutions in states like West Virginia and Pennsylvania are examining in depth for critical mineral recovery. Research institutions in coal country are examining ways to recover rare earth minerals (a category of critical minerals that are difficult to find naturally in concentrated quantities) from coal waste tailings.[34] If this innovative research can be successfully scaled, it opens up another path to critical mineral procurement while cleaning up coal waste.

Technology Transfer

Technology transfer is the process of sharing technology, knowledge, skills, and innovations from one organization or country to another. Fostering technology transfer between allied nations and research institutions is increasingly beneficial as national economies become more intertwined. It encourages international cooperation, strengthening international relationships. It accelerates the commercialization of new technologies, driving economic development. It can also synthesize development designs for broader adaptation, modifying technology to fit the specific needs, standards, or environmental conditions of partner countries and institutions.[35]

Technology transfer can be established via direct transfer, licensing agreements, joint ventures, research exchange programs, and government partnerships.[36] This exchange of knowledge and research should be encouraged to accelerate the development of innovative technologies.

Recommendations

1. Create More Uniformity in Material Regulations

The transportation of EV batteries headed to recycling facilities requires adherence to the regulations of each jurisdiction it passes through. Since the regulations for the transportation and management of hazardous materials has significant variation across jurisdictions, it can deter recycling initiatives and slow down acquisition of material feedstock that is crucial to supporting the recycling industry. The working group recommends harmonizing all standards throughout the U.S. across federal, state and tribal lands that maintains best practices for secure management of hazardous materials while removing the burden of navigating inconsistent regulations.

2. Design State-Level Extended Producer Responsibility Programs

Extended Producer Responsibility (EPR) programs are designed to promote sustainability and reduce waste, but their effectiveness depends on design and implementation. To avoid ossification and ensure continuous improvement, EPR programs need to be flexible and responsive to technological advancements, regional market changes, and evolving environmental needs. Regular evaluation and adjustment of these programs can help mitigate potential drawbacks and enhance their overall effectiveness. Focusing on state-level EPR programs can create more flexibility in implementation and specificity to address the specific needs and challenges faced by states.

3. Prioritize Targeted Research Endeavors

Research and development with clear and specific goals generally have better chances of success. For example, place-based thinking can lead to more targeted innovations designed to utilize specific local conditions to meet broader goals. An example of this focused application can be found in the coal country research institutions that are examining how to recover rare earth minerals from coal waste tailings.

Additionally, innovations in technology and material sciences face many barriers to commercialization. Therefore, it is strongly recommended that research with greater scalability potential be prioritized.

4. Include Circularity Considerations in New Battery Designs

It is important to consider recyclability in the development stage of new and evolving technologies. With the solid state and sodium-ion battery chemistries still in prototype and development stages, they provide an excellent opportunity to incorporate circularity considerations into the next generation of battery chemistries.

5. Participate in International Partnerships for Technology Transfer

Sharing technology and collaborating with partners can enhance research efficiency and reduce costs. The benefits of these partnerships can include accelerated advancements in mineral recovery, supply chain circularity, and environmental protections.

6. Utilize Automated Sorting Technologies

Automated sorting technologies like XRF remove labor constraints to expand recycling efforts. As mentioned in the discussion, they can maintain 95% or higher recovery rates of valuable critical minerals from recycled lithium-ion batteries.[37]

Signatories Page

This document represents the collective effort of the working group, reflecting a range of perspectives and contributions. Each participant retains the right to their own opinions and reservations regarding specific aspects of the white paper. Endorsement of this document does not imply unanimous agreement with all content but rather signifies support for the overall objectives of the working group.

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Appendix A

Sample List of Products in U.S. States with Extended Producer Reliability (EPR) Programs[38]

California	• Electronics (E-Waste) • Batteries* • Paint • Mattresses	• Sharp Objects • Mercury-Containing Materials • Pharmaceuticals
Oregon	• Electronics • Batteries • Paint • Packaging	• Pharmaceuticals • Paper Products • Mercury-Containing Products
Washington	• Electronics • Batteries • Paint • Packaging	• Pharmaceuticals • Household Hazardous Waste
Maine	• Electronics • Batteries • Paint • Mattresses	• Packaging • Pharmaceuticals
Vermont	• Electronics • Batteries • Paint • Mattresses	• Packaging • Pharmaceuticals • Mercury-Containing Products
New York	• Electronics • Batteries* • Paint • Packaging	• Pharmaceuticals • Used Tires
Connecticut	• Electronics (E-Waste) • Batteries • Paint • Mattresses	• Pharmaceuticals • Mercury-Containing Products • Used Tires

*These states currently only have local municipal programs and are exploring ways to expand to the state level.

Appendix B

The 2022 list of critical minerals and their uses includes the following:

- Aluminum, used in almost all sectors of the economy
- Antimony, used in lead-acid batteries and flame retardants
- Arsenic, used in semi-conductors
- Barite, used in hydrocarbon production.
- Beryllium, used as an alloying agent in aerospace and defense industries
- Bismuth, used in medical and atomic research
- Cerium, used in catalytic converters, ceramics, glass, metallurgy, and polishing compounds
- Cesium, used in research and development
- Chromium, used primarily in stainless steel and other alloys
- Cobalt, used in rechargeable batteries and superalloys
- Dysprosium, used in permanent magnets, data storage devices, and lasers
- Erbium, used in fiber optics, optical amplifiers, lasers, and glass colorants
- Europium, used in phosphors and nuclear control rods
- Fluorspar, used in the manufacture of aluminum, cement, steel, gasoline, and fluorine chemicals
- Gadolinium, used in medical imaging, permanent magnets, and steelmaking
- Gallium, used for integrated circuits and optical devices like LEDs
- Germanium, used for fiber optics and night vision applications
- Graphite , used for lubricants, batteries, and fuel cells
- Hafnium, used for nuclear control rods, alloys, and high-temperature ceramics
- Holmium, used in permanent magnets, nuclear control rods, and lasers
- Indium, used in liquid crystal display screens
- Iridium, used as coating of anodes for electrochemical processes and as a chemical catalyst
- Lanthanum, used to produce catalysts, ceramics, glass, polishing compounds, metallurgy, and batteries
- Lithium, used for rechargeable batteries
- Lutetium, used in scintillators for medical imaging, electronics, and some cancer therapies
- Magnesium, used as an alloy and for reducing metals
- Manganese, used in steelmaking and batteries
- Neodymium, used in permanent magnets, rubber catalysts, and in medical and industrial lasers

- Nickel, used to make stainless steel, superalloys, and rechargeable batteries
- Niobium, used mostly in steel and superalloys
- Palladium, used in catalytic converters and as a catalyst agent
- Platinum, used in catalytic converters
- Praseodymium, used in permanent magnets, batteries, aerospace alloys, ceramics, and colorants
- Rhodium, used in catalytic converters, electrical components, and as a catalyst
- Rubidium, used for research and development in electronics
- Ruthenium, used as catalysts, as well as electrical contacts and chip resistors in computers
- Samarium, used in permanent magnets, as an absorber in nuclear reactors, and in cancer treatments
- Scandium, used for alloys, ceramics, and fuel cells
- Tantalum, used in electronic components, mostly capacitors and in superalloys
- Tellurium, used in solar cells, thermoelectric devices, and as alloying additive
- Terbium, used in permanent magnets, fiber optics, lasers, and solid-state devices
- Thulium, used in various metal alloys and in lasers
- Tin, used as protective coatings and alloys for steel
- Titanium, used as a white pigment or metal alloys
- Tungsten, primarily used to make wear-resistant metals
- Vanadium, primarily used as alloying agent for iron and steel
- Ytterbium, used for catalysts, scintillometers, lasers, and metallurgy
- Yttrium, used for ceramic, catalysts, lasers, metallurgy, and phosphors
- Zinc, primarily used in metallurgy to produce galvanized steel
- Zirconium, used in the high-temperature ceramics and corrosion-resistant alloys.

Source: U.S. Geological Survey