U.S. Department of Energy
Advanced Research Projects Agency – Energy (ARPA-E)

Request for Information (RFI)
DE-FOA-0002213
on
Biotechnologies to Ensure a Robust Mineral Supply Chain for Clean Energy

Introduction

With increased global competition for minerals in emerging tech, defense, and clean energy applications, any shortage of critical mineral resources "constitutes a strategic vulnerability for the security and prosperity of the United States."[1] The U.S. Department of the Interior (DOI) has recently published a list of such materials, which include[2]:

- **Rare Earth Elements (REEs)** consisting of the Lanthanide series: Lanthanum, Cerium, Praseodymium, Neodymium, Promethium, Samarium, Europium, Gadolinium, Terbium, Dysprosium, Holmium, Erbium, Thulium, Ytterbium and Lutetium, as well as Yttrium and Scandium;
- **The Platinum Group Metals (PGMs):** Iridium, Osmium, Palladium, Platinum, Rhodium, Ruthenium; and
- **Other critical materials:** Aluminum (bauxite), Antimony, Arsenic, Barite ($BaSO_4$), Beryllium, Bismuth, Cesium, Chromium, Cobalt, Fluorspar (CaF_2), Gallium, Germanium, Graphite (natural), Hafnium, Helium, Indium, Lithium, Magnesium, Manganese, Niobium, Potash, Rhenium, Rubidium, Strontium, Tantalum, Tellurium, Tin, Titanium, Tungsten, Uranium, Vanadium, and Zirconium.

Besides the critical metals identified by DOI, other base transition metals of interest for the U.S. Department of Energy's Advanced Research Projects Agency – Energy (ARPA-E) are Nickel (Ni) and Copper (Cu). In 2018, the global Ni demand for Li-ion batteries was 85,000 tons and this is expected to increase by 30-40% per year[3]. The U.S. Nickel production represents less than 1% (19,000 tons) of the total global production. In contrast, in 2018, Indonesia and the Philippines were the major global Ni raw

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[1] "Interior Seeks Public Comment on Draft List of 35 Minerals Deemed Critical to U.S. National Security and the Economy", U.S. Department of the Interior press release, February 16, 2018. [https://www.doi.gov/pressreleases/interior-seeks-public-comment-draft-list-35-minerals-deemed-critical-us-national]

[2] "Final List of Critical Minerals 2018". U.S. Department of the Interior, Office of the Secretary, Federal Register/ Vol. 83, No 97 p. 23295 May 18, 2018 [https://www.govinfo.gov/content/pkg/FR-2018-05-18/pdf/2018-10667.pdf]

[3] Written Testimony of Simon Moores, Managing Director, Benchmark Mineral Intelligence, before US Senate Committee on Energy and Natural Resources, February 5, 2019. [https://www.energy.senate.gov/public/index.cfm/files/serve?File_id=9BAC3577-C7A4-4D6D-A5AA-33ACDB97C233]

material producers[4] at 560,000 tons and 340,000 tons, respectively.

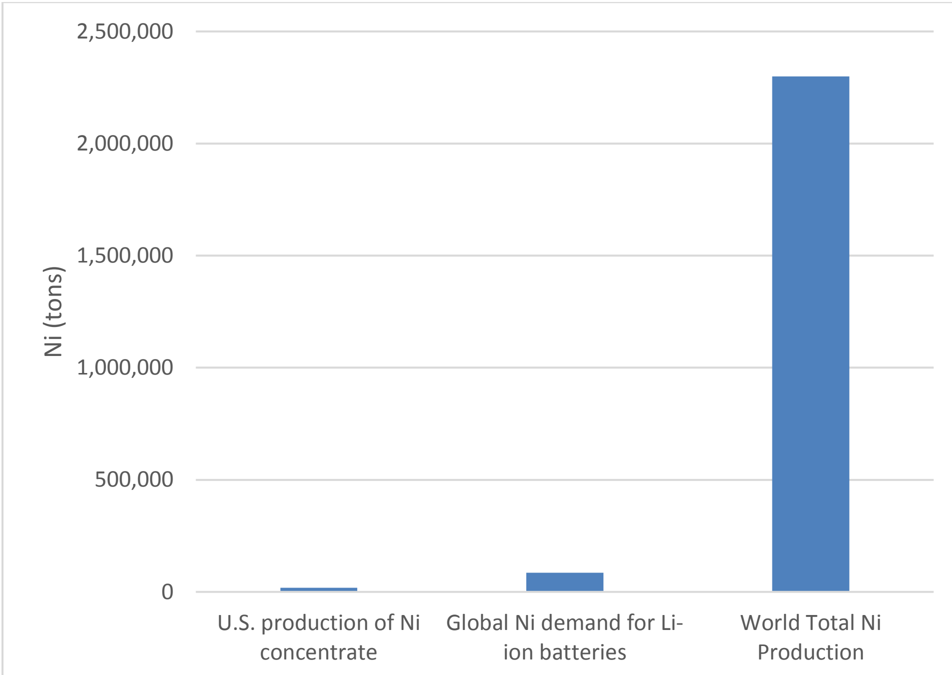

Figure 1. Comparison of the total U.S. production of Ni, the global demand for Ni in Li-ion batteries and the total global production of Niall for 2018 [Graph plotted with information in reference provided in footnote 3 and 4].

While the U.S. is the third largest global Copper producer - with 1.2 million tons produced in 2018 - just behind Chile and Peru[5], the unique thermal and electrical properties of this metal make it a crucial element for energy efficiency applications. The issues around this material are the increase in Cu production costs due to declining domestic ore grades and the associated energy and environmental concerns around Cu extraction and processing.

ARPA-E sees novel, potentially transformative technical opportunities/approaches to recovering critical materials from new approaches to biomining. Biomining is a process where an electron interplay takes place between metal-containing materials (like ores) and microorganisms (such as prokaryotes) with the objective to facilitate the solubilization and recovery of metals. This biotechnological process could significantly facilitate the extraction of redox-active critical metals from subterranean ore bodies, landfilled metal-containing wastes, spent catalysts and other sources.. Though long and widely practiced for the extraction of metals (Au, Cu in particular)[6] from leach piles, recent developments in 1) microbial consortia mechanisms, 2) genetic modification/directed evolution and 3) identification of

[4] U.S. Geological Survey, 2019, Mineral commodity summaries 2019: U.S. Geological Survey, p. 53, 113 [https://doi.org/10.3133/70202434]

[5] Ibid

[6] D. B. Johnson "The Evolution, Current Status and Future Prospects of Using Biotechnologies in the Mineral Extraction and Metal Recovery Sectors", *Minerals* 2018, 8, p. 343. [https://doi.org/10.3390/min8080343]

extremophiles, low/high pH (pH < 1 or >10) and high temperature (~ 80 °C) may help improve bioreactor productivity, contamination issues and overall process economics.. For example, Reed et al. recently showed that *G. oxidans* (B58) was effective in leaching REEs like Lanthanum (La) from spent FCC catalysts[7] with a bioleaching yield of 49%. A subsequent study[8] by the same leading author (D. Reed) showed bioleaching yield improvements by optimizing agitation intensity, oxygen levels, glucose and nutrient concentrations in batch (56% yield) and continuous bioreactor (51% yield) configurations. Another study[9] showed that bioleaching of coal fly ash using a culture supernatant of *C. bombicola* strain led to ~ 60% mineral extraction, where Arsenic (As), Molybdenum (Mo), Ytterbium (Yb), and Erbium (Er) were amongst the highest recovered.

ARPA-E is interested in surveying bio-based ideas across the entire supply chain of critical materials and other metals (Ni, Cu), including exploration, mining, extraction, processing, refining and recycling/recovery of such materials. ARPA-E requests responses focusing on the feedstock supply for successfully meeting the domestic demand, economic feasibility and environmental sustainability of critical materials.

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below. Please note, in particular, that the information you provide will be used by ARPA-E solely for program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME.**

Purpose and Need for Information

The purpose of this RFI is solely to solicit input for ARPA-E consideration to inform the possible formulation of future research programs. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI without any attribution to the source. This RFI provides the broad research community with an opportunity to contribute views and opinions.

REQUEST FOR INFORMATION GUIDELINES

No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E may contact respondents to request clarification or seek additional information relevant to this RFI. All responses provided will be considered, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents should clearly mark any information in the response to this RFI that might be considered proprietary or confidential. Information labeled proprietary or confidential will not be released by DOE, but may be used to inform ARPA-E's planning.**

Depending on the responses to this RFI, ARPA-E may consider the rapid initiation of one or more funded collaborative projects to accelerate along the path towards commercial deployment of the energy

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[7] D. Reed, Y. Fujita, D.L. Daubaras, Y. Jiao, V. S. Thompson "Bioleaching of rare earth elements from waste phosphors and cracking catalysts", *Hydrometallurgy* 166 (2016) p. 34 [https://doi.org/10.1016/j.hydromet.2016.08.006]

[8] V. S. Thompson et al. "Techno-economic and Life Cycle Analysis for Bioleaching Rare-Earth Elements from Waste Materials" , ACS Sustainable Chem. Eng. (2018) 62 p.1602 [https://doi.org/10.1021/acssuschemeng.7b02771]

[9] S. Park and W. Liang "Bioleaching of trace elements and rare earth elements from coal fly ash" *Int J Coal Sci Technol* (2019) 6(1):74–83 https://doi.org/10.1021/acssuschemeng.7b02771

technologies described generally above.

Responses to this RFI should be submitted in PDF format to the email address **ARPA-E-RFI@hq.doe.gov** by **5:00 PM Eastern Time on December 17, 2019**. Emails should conform to the following guidelines:

- Please insert "Responses for Critical Minerals RFI" in the subject line of your email, and include your name, title, organization, type of organization (e.g. university, non-governmental organization, small business, large business, federally funded research and development center (FFRDC), government-owned/government-operated (GOGO), etc.), email address, telephone number, and area of expertise in the body of your email.
- Responses to this RFI are limited to no more than 10 pages in length (12 point font size).
- Responders are strongly encouraged to include preliminary results, data, and figures that describe their potential methodologies.

Questions

Please provide responses and information about any of the following. We do not expect any one respondent to answer all, or even many, of these prompts. Simply indicate the question number in your response. Citations are encouraged as appropriate. Respondents are also welcome to address other relevant avenues/technologies that are not outlined below.

1. ***Biomining microbiology and engineering configuration of the deployed biological system***

   In regards to the microbiology:

   a) Is there a need to identify new microorganisms that can more effectively exchange electrons with critical materials? Can a cell-free approach be suitable for critical metals recovery? How can we increase the rate of metal resistance/adaptation by the microorganism(s)?
   b) Where are the knowledge gaps in regards to the understanding of the molecular mechanism of electron transfer?
   c) Is there a need to advance analytical techniques (e.g., proteins and protein complexes molecular structures imaging) to better understand the fundamentals of biomining?
   d) Are there potential extremophiles that have either be found to, or can be modified to, perform metal extractions in high temperature, highly alkaline/acidic pH conditions?

   In regards to the engineering configuration:

   e) Beyond Continuous Stirred Tank Reactors (CSTRs) and heap reactors[10], what novel approaches in reactor design can increase the yield of extraction of critical metals while reducing energy consumption and environmental impacts?
   f) What are the anticipated scale-up issues of novel reactor design?
   g) Which critical metals can be recovered using this approach?

[10] A heap reactor is a configuration where mineral sources (e.g., ores) are stacked over an impermeable pad and a solvent, called the lixiviant, is employed to wet the materials to produce a metal loaded solution, called the leachate.

h) What opportunities are there for the extension of hydrolytic fracturing advancements to facilitate deep *in-situ* biomining?

2. ***Intensification***. What disruptive approaches can be applied to the supply chain of these critical materials to intensify their production (e.g., deep *in situ* bio-mining, combinations with electrochemistry, bioremediation/biomining)?

3. ***Missing Critical Materials.*** Beyond the critical materials identified in this RFI, are there other materials that ARPA-E should consider as critical in the development of clean energy technologies (e.g., grid-scale energy storage, electric vehicles, motors for wind turbines, catalysts, etc.)? Why?

4. ***Selection of Critical Minerals.*** Which mineral(s) identified in this RFI and in your response to Q. 3 (if any) should be prioritized for the development of clean energy technologies? Why?

5. ***Sources of Critical Materials.*** Discuss the availability of U.S. domestic resources to increase access to these critical minerals. For example, deep sea resources, landfills[11,12], e-waste[13,14], Energy-from-Waste ash, recycling[15], mine tailings, deep ore deposits, other[16].

6. ***Extraction of Critical Materials***. What are other novel/unconventional biological approaches to the extraction of critical materials that can reduce mining energy consumption[17], eliminate or reduce operational hazards, improve mining economics and/or reduce environmental impacts. For example, macrobes (shipworms[18])?

7. ***REE-containing components/applications***. Are there new applications or fabrication methods requiring the use of REEs or other critical metals that would result in significant increases in domestic consumption?

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[11] S. C. Gutiérrez- Gutiérrez, F. coulon, Y. Jiang, S. Wagland "Rare earth elements and critical metal content of extracted landfilled material and potential recovery opportunities" *Waste Management* 42 (2015) p. 128 [https://doi.org/10.1016/j.wasman.2015.04.024]

[12] J. Burlakovs, et al. "On the way to 'zero waste' management: Recovery potential of elements, including rare earth elements, from fine fraction of waste", *Journal of Cleaner Production* 186 (2018) p. 81 [https://doi.org/10.1016/j.jclepro.2018.03.102]

[13] J. Hobohm and K. Kuchta "Innovative recovery strategies of rare earth and other critical metals from electric and electronic waste"*, XXXV Reunión de la Sociedad Española de Mineralogía* Huelva June 30- July 3, 2015. [http://www.ehu.eus/sem/seminario_pdf/SeminSEM_12.Hobohm.prov.pdf]

[14] Oak Ridge National Laboratory. "Hard Disk Drive Dismantlement for Critical Material Recovery". Invention Reference Number 201804249. [https://www.ornl.gov/technology/201804249-0]

[15] Ames Laboratory. "Acid-free rare-earth magnet recycling". [https://www.ameslab.gov/techtransfer/acid-free-rare-earth-magnet-recycling]

[16] J.R. Dodson, A.J. Hunt, H.L. Parker, Y. Yang, J.H. Clark "Elemental sustainability: Towards the total recovery of scarce metals", *Chemical Engineering and Processing* 51 (2012) p. 69 [https://doi.org/10.1016/j.cep.2011.09.008]

[17] Mining Industry Energy Bandwidth Study. Industrial Technologies Program U.S. DOE (2007) p. 18 [https://www.energy.gov/sites/prod/files/2013/11/f4/mining_bandwidth.pdf]

[18] J. R. Shipway, et al. "A rock-boring and rock-ingesting freshwater bivalve (shipworm) from the Philippines" *Proc. R. Soc. B* 286: 20190434 p.1. [https://royalsocietypublishing.org/doi/pdf/10.1098/rspb.2019.0434]