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

Request for Information (RFI)
DE-FOA-0002469
On
CO_2 Mineralization to Enhance the Extraction of Energy-Relevant and Commodity Minerals

Introduction

The purpose of this RFI is to solicit input for a potential future ARPA-E research program focused on novel, potentially transformative technical opportunities and approaches to **liberate minerals relevant to our energy infrastructure while concurrently mineralizing carbon dioxide**.

With increased global competition for minerals in emerging technology, 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; however, in addition to the critical metals identified by DOI, the U.S. Department of Energy's Advanced Research Projects Agency – Energy (ARPA-E) is also interested in other energy-relevant base transition metals, specifically those listed in table 1 below.

Critical Mineral	**Energy Relevance**
Nickel (Ni)	Rechargeable nickel-cadmium and nickel-metal hydride batteries
Zinc	Zinc-air batteries
Chromium	Metal alloy for turbines
Copper	Energy efficient electricity conduction
Phosphorus	Iron-phosphate batteries

Table 1. Critical minerals with identified applications in energy.

Figure 1 forecasts significant growth in nickel demand over the next 20 years and indicates a transition of the United States' energy infrastructure away from fossil fuels and toward renewably generated electricity. This transition is already manifesting in the automobile industry, where advancements in battery manufacturing have enabled the proliferation of electric vehicles in an industry traditionally dominated by fossil fuels. In order to facilitate this shift in energy infrastructure and enhance domestic energy security, the U.S must develop improved methods to secure a robust supply of these energy-relevant and commodity minerals.

[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]

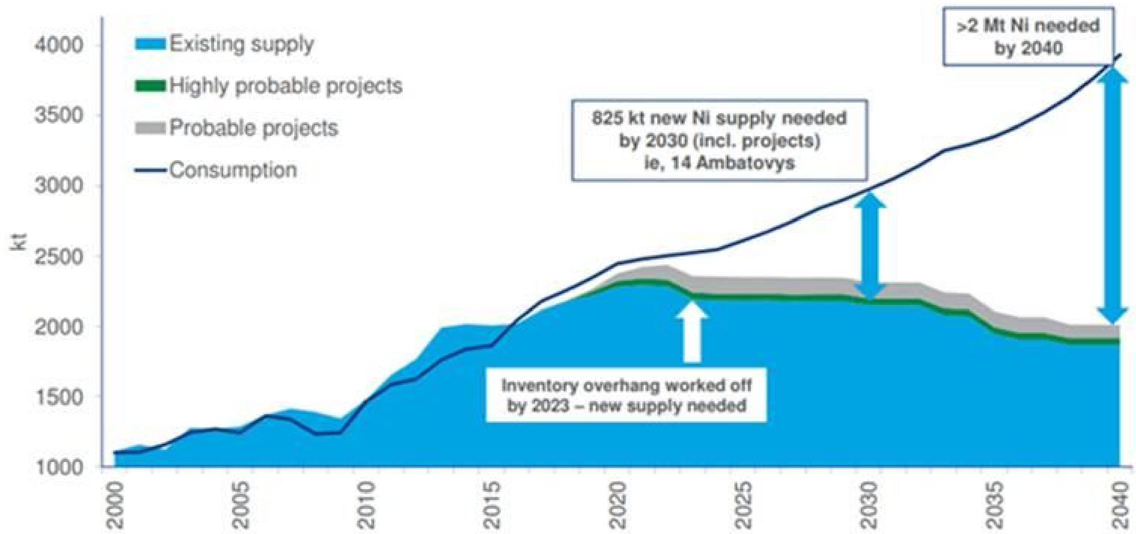

Figure 1. Nickel demand forecast to 2040 compared to projected existing supply and planned projects[2].

Carbon mineralization is a naturally occurring chemical process wherein CO_2 reacts with the alkaline earth metal cations found in mafic, ultramafic and other ore bodies to form carbonate minerals. Recently, there has been significant interest in using this reaction as a route to sequester CO_2 directly from the air or from industrial activities. There have also been significant advancements in carbon capture and storage (CCS) either through capture of stack emissions of CO_2 from power generation or industrial sources or direct air capture (DAC) of atmospheric CO_2. Current CCS and DAC deployments typically aim to inject the captured CO_2 into underground formations such as depleted oil and gas fields or saline aquifers[3]. These geological methods of storage have the advantage of being relatively low cost. However, there are significant challenges related to permanence, monitoring and verification, and a general lack of clarity around potential long-term risks of these geological methods.

Carbon mineralization as a strategy to both sequester CO_2 and liberate energy-relevant minerals represents a significant opportunity to address the growing need for these minerals while concurrently contributing to a reduction in green house gases. However, there are still significant knowledge gaps in the application of this novel technology at an industrial scale. For example, Gadikota *et al.*[4] found that as olivine rock is dissolved and carbonated, it undergoes significant morphological changes that subsequently affect its reactivity with CO_2, including changes in pore volume, surface area, and particle size. Ultimately, they found that under high-temperature, high-pressure CO_2 conditions, and in the presence of 0.64 M $NaHCO_3$, approximately 70% of olivine was carbonated after 3 hours. These authors emphasized the need for further research into the multitude of chemical and physical factors that underlie these geochemical processes which will enable a more accurate assessment of the potential for economic and environmental amelioration.

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[2] Source: Wood Mackenzie [http://www.mining.com/electric-vehicle-demand-will-double-nickel-price-soon-2022/]

[3] V. Romanov et al. “Mineralization of Carbon Dioxide: Literature Review”, ChemBioEng Rev 2015, 2, No. 4, 231–256

[4] G. Gadikota et al. “Chemical and Morphological Changes during Olivine Carbonation for CO2 Storage in the Presence of NaCl and NaHCO3”, *Phys.Chem.Chem.Phys.,* 2014, 16, 4679. DOI: 10.1039/c3cp54903h

ARPA-E requests responses focusing on how CO_2 from power plants, industrial sources, or the atmosphere can be leveraged to improve mining practices in order to successfully meet the growing domestic demand, economic feasibility, and environmental sustainability of critical materials (CMs). ARPA-E is predominantly (not exclusively) interested in approaches targeting the recovery of nickel, cobalt, and chromium deposits in mafic or ultramafic rock formations.

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 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 February 18, 2021**. Emails should conform to the following guidelines:

- Please insert "Responses for CO_2 Mineralization to Enhance the Extraction of Energy-Relevant and Commodity 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. ARPA-E does 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. ***Carbon mineralization chemistry and engineering of the deployed technology.***
   a) Regarding supply of CO_2 to extractive operations: Does CO_2 mineralization have the potential to improve the liberation and mining of critical minerals? Why or why not?
   b) What is the effect of CO_2 concentration and conditions on mineralization potential?

CO_2 concentration	CO_2 Source examples	Effect of concentration on mineralization potential
Low (e.g., 410 ppm)	Atmospheric CO_2	
Medium (e.g., 4-22 wt.%)	Power plant (NG, coal, biomass), DAC, cement kiln, metal blast furnace	
High (e.g., > 95 wt.%)	CCS exit stream, corn-to-ethanol fermentation	

   c) What are the available methods for supplying CO_2 to a mine site? What engineering/technological challenges are associated with deploying a concentrated CO_2 stream to a mine site?
   d) Is there a significant potential for permanent carbon sequestration at the scale of at least megatons per year using mineralization technologies?
   e) What are the knowledge gaps regarding carbonation chemistry? Is there a need to identify additional significant thermo-, electro-, mechano-, and/or biochemical approaches to improve the efficiency of CO_2 mineralization?
   f) What new metrology capabilities are required to quantify CO_2 uptake, deposition composition, and permanence?
   g) Beyond CO_2 mineralization, are there other applications for CO_2 within the mining supply chain that enable increased product yields, improve energy efficiency, or ameliorate emissions?

   Regarding processing and mineralization of ore bodies:

   h) Where are the best sites to deploy CO_2 mineralization technology for maximum benefit? What is the minerology, geology, and geography of these deposits? How does variation in ore quality affect processing efficiency? What developments are need to accurately map and characterize appropriate deposits?

i) Should target elements be collected as metals, carbonates, oxides, or other forms and why?
j) Is it possible to avoid or reduce tailings using a CO_2 mineralization approach?
k) What are the most significant thermo-, electro-, mechano-, and/or biochemical factors that limit mineralization rate? What are some of the current and proposed methods for improving the rate of CO_2 mineralization?
l) What are the practical considerations: toxicity, supply chain, pollution, etc. and benefits associated with the extraction of energy-relevant minerals using CO_2, specifically Cu, Ni, Zn, Mn, Cr, and Co?
m) Are there other attractive commodity minerals/elements found in CO_2 reactive deposits that should be pursued?

2. ***Methods for carbonation and mineral liberation.***
   a) What knowledge gaps exist for performing CO_2 mineralization *in situ*?
   b) What knowledge gaps exist for performing CO_2 mineralization *ex situ*?
   c) What challenges or advantages do *in situ* versus *ex situ* approaches to mineralization pose from technical, economic, or lifecycle perspectives?
   a) Are there additional compounds/catalysts that would be required to complete or enhance mineralization?

3. ***Selection of Energy Relevant Minerals****.* Which mineral(s) identified in this RFI should be prioritized for the development of clean energy technologies? Why? Which mineral(s) should be prioritized for liberation via CO_2 mineralization? Why?
4. ***Commercialization of proposed technology.***
   a) Are there significant hurdles to scaling up this technology?
   b) How does the implementation of CO_2 mineralization technology affect short-term and long-term profitability of mining operations?
   c) Beyond the mining industry, what other industries/processes might be improved through the introduction of carbon mineralization?
5. ***Market forces affecting demand for Energy-Relevant Minerals (or other CMs).***
   a) Many projections have been made (BNEF, EIA, etc.) about the future demand for energy-relevant minerals and other critical materials. Environmental, social, financial, political factors have been described. What, if anything, are these models missing?
   b) What is the state of current domestic mineral sources? What are current and predicted trends when it comes to ore quality?
   c) How do energy storage and generation fit into the overall economics of the mining supply chain? What are the challenges and costs associated with replacing energy from fossil fuels with "clean" energy from wind, solar, geothermal, etc.? How would such a switch affect both the economics and environmental impact of minerals extraction?
  d) Discuss the potential impact of battery and electronics recycling on future demand for the targeted elements.