2023

CRITICAL MINERALS AND MATERIALS PROGRAM

PROJECT PORTFOLIO

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

DISCLAIMER

CONTENTS

INTRODUCTION

The Critical Minerals and Materials (CMM) Program aims to rebuild U.S. leadership in extraction and processing technologies for the production of critical minerals and materials (CMM) that include rare earth elements (REE)[1], critical minerals (originally defined by the U.S. Geological Survey [USGS][2]), and materials deemed critical by the Department of Energy (DOE)[3], from unconventional resources and secondary byproduct sources to support an economical, environmentally benign, and geopolitically sustainable U.S. domestic supply chain.

Unconventional CMM resources include any resource from a geologic or secondary byproduct host that is distinctive from the mechanisms resulting in conventional, established deposits. Unconventional CMM can be sourced from in situ geologic deposits or from secondary byproducts of anthropogenic processes. These sources require revised or new methods and models to characterize and assess that focus on the unique source and temporal controls resulting in these deposits.

Examples of unconventional and secondary byproduct sources include:

- Sedimentary deposits such as coal, black shale, tonsteins (clay-altered volcanic ash), coal underclays, and marine phosphates.
- Secondary byproducts derived from mining and fossil-energy related waste streams such as produced water, coal fly ash, acid mine drainage, and alloy production residues.

Visit a story map on Unlocking the Potential of Unconventional Critical Mineral Resources for more information

The NETL CMM Program is focused on the following goals:

- Validate the technical and economic feasibility of domestic small pilot-scale facilities to produce high-purity CMM from carbon ore and coal-based resources.
- Produce 1–3 tonnes/day of high-purity mixed rare earth oxides/salts in domestic demonstration-scale facilities and refine to metals or alternative user-specified products as required for use in the CMM supply chain using coal-based and alternative resources as feedstock materials.
- Perform a regional assessment and production of CMM and novel high-value, nonfuel carbon-based products covering the entire United States.

1 Rare earth elements: (lanthanide series) lanthanum, cerium, praseodymium, neodymium, (promethium,) samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium. Scandium and yttrium are often also included.

2 Critical minerals (USGS): aluminum (bauxite), antimony, arsenic, barite, beryllium, bismuth, cesium, chromium, cobalt, fluorspar, gallium, germanium, graphite (natural), hafnium, indium, lithium, magnesium, manganese, nickel, niobium, platinum group metals, potash, the rare earth elements group, rhenium, rubidium, scandium, tantalum, tellurium, tin, titanium, tungsten, vanadium, yttrium, zinc, and zirconium.

3 Critical materials (DOE): aluminum (metal), cobalt, copper, dysprosium, fluorine, gallium, graphite, iridium, lithium, magnesium, neodymium, nickel, platinum, praseodymium, silicon, silicon carbide, electrical steel, terbium, and uranium.

Rare Earth Elements and Critical Minerals

Rare earth elements (Figure 1) are essential materials in a broad range of technologies significant to national security, energy, medical, and consumer products (Figure 2). REE occur throughout the earth's crust, commonly at low concentrations. They are not found in an isolated form readily available for extraction, but are distributed throughout a variety of minerals, and are also found in coal and coal by-products. REE-bearing mineral deposits are relatively rich in either light rare earth elements (LREE) or heavy rare earth elements (HREE), with LREE generally more abundant. The environmental footprint created by conventional REE processing techniques has long been a key consideration in determining where these elements are mined and subsequently produced.

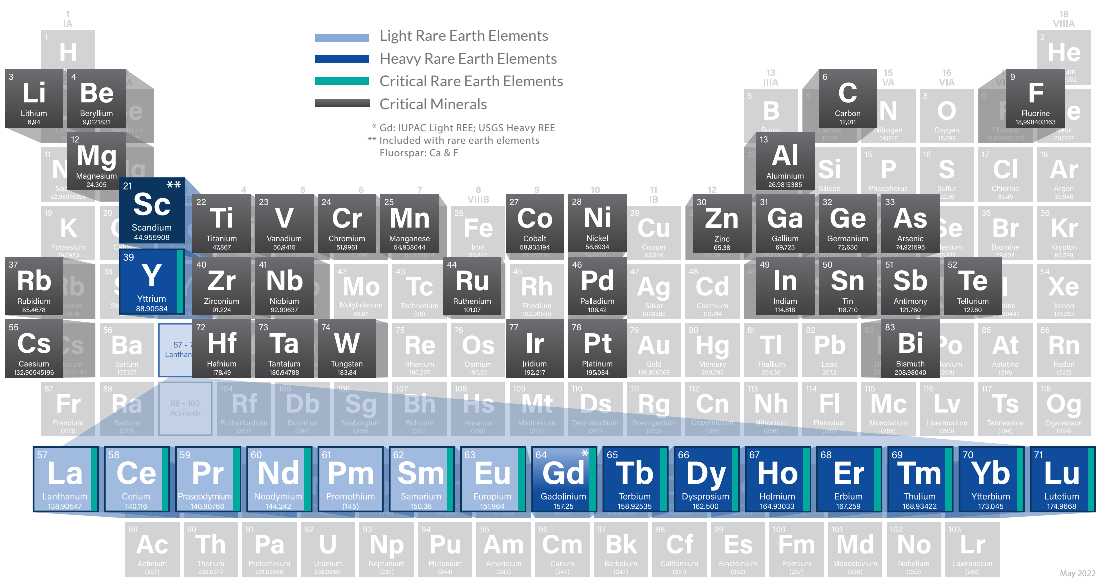


Figure 1. Elements, minerals, and materials deemed "critical" by the USGS and DOE.

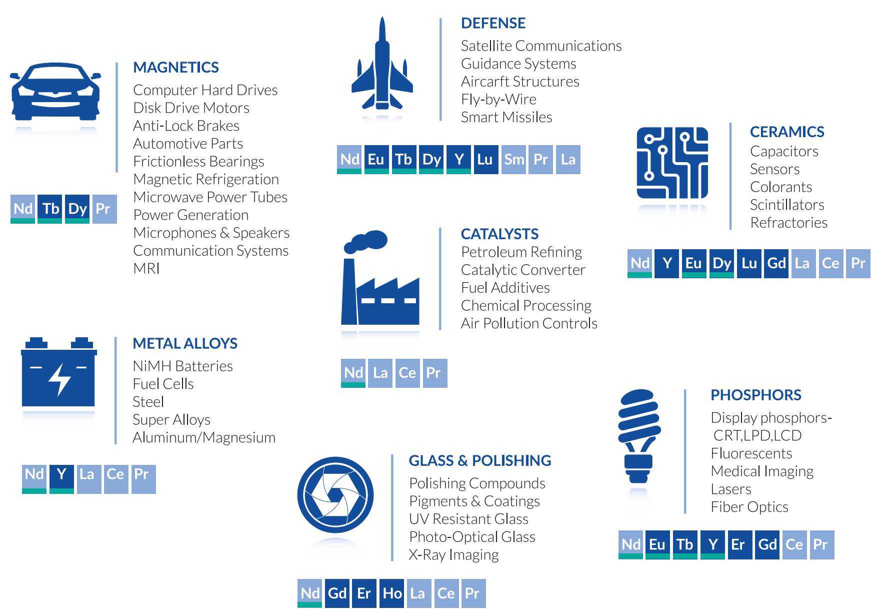


Figure 2. Rare earth element applications.

For decades the United States was the leading global producer of REE dating back to the 1960s until approximately 1998 when United States production significantly declined and China became the dominant global supplier (Figure 3). The nation currently imports over 74% of its rare earth oxides directly from China, with portions of the remainder indirectly sourced from China through other countries. Similarly, the United States imports more than half of its annual consumption for 31 of the 35 critical minerals and has no domestic production for 14 critical minerals, leaving it dependent on imports to meet demand. The DOE's list of critical materials overlaps many of those critical minerals described by the USGS and include other clean energy technology materials vulnerable to supply chain disruption.

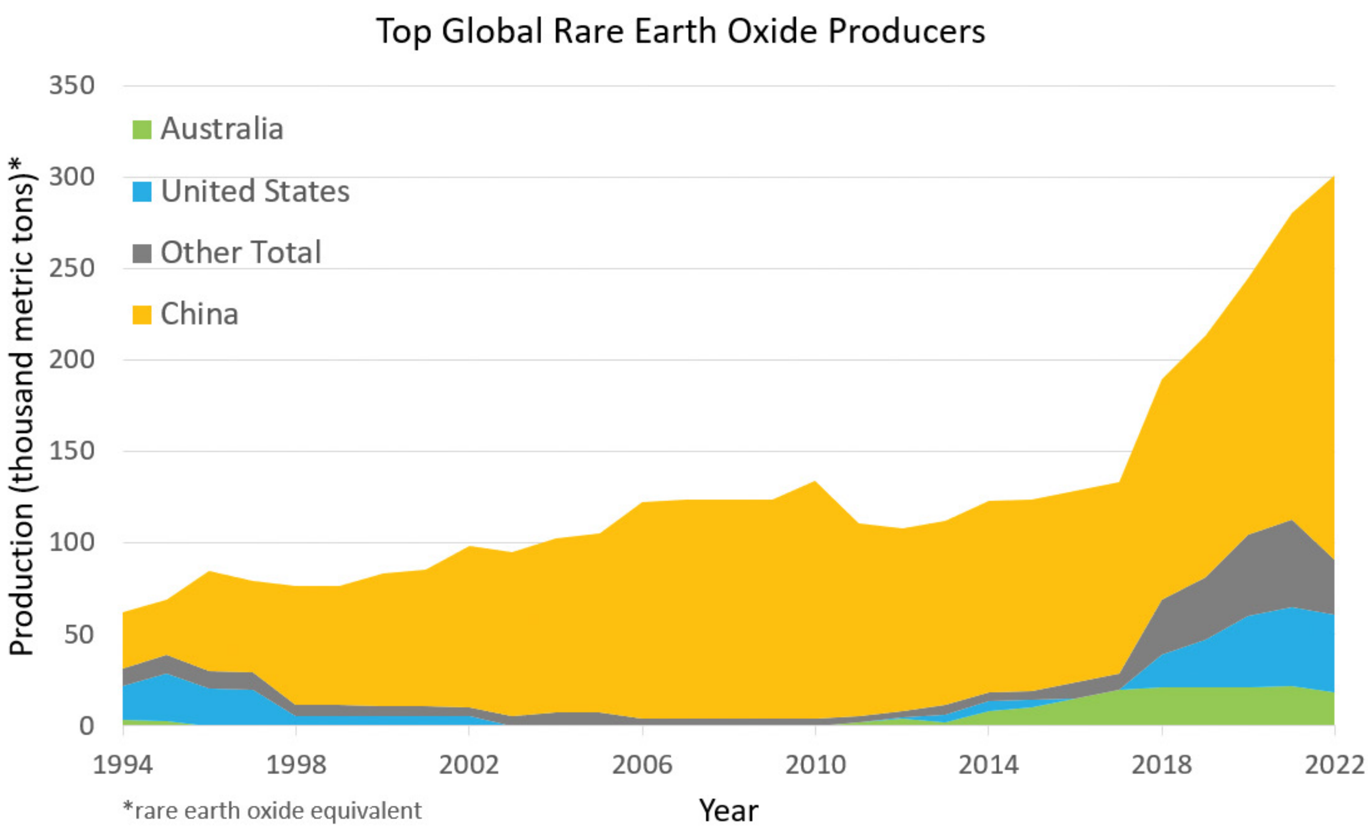


Figure 3. Major international rare earth suppliers.

History of the Critical Minerals and Materials Program

Transitioning the production of CMM and their associated supply chains back to the United States is a strategic priority as evidenced by recently enacted and proposed legislation and several Executive Orders such as President Biden's declaration that the supply chain threat to critical minerals is a national emergency.[4,5] Consequently, research, development, and demonstration (RD&D) efforts to create new domestic sources of CMM have been accelerated with the goal of making our domestic supply chains more resilient. The current CMM program had its origin in 2014.

2014 - Initial assessment under Feasibility of Recovering Rare Earth Elements Program

To address the challenge of leading our nation to secure national independence from REE offshore reliance, in 2014 DOE's Office of Fossil Energy and Carbon Management (FECM), and NETL performed an initial assessment under its Feasibility of Recovering Rare Earth Elements Program to assess the potential recovery of REEs from carbon ore and coal byproducts including run-of-mine coal, coal refuse (mineral matter that is removed from coal prior to shipment), clay/sandstone over/under-burden materials, ash (coal combustion residuals), and aqueous effluents such as acid mine drainage (AMD), as well as associated solids and precipitates resulting from AMD treatment.

2015 to 2018 – Initiation of a multi-year RD&D effort to recover REEs

After reporting its findings in the DOE 2015 Report to Congress , DOE initiated a multi-year RD&D effort to demonstrate both the technical feasibility and economic viability of extracting, separating, and recovering REEs from these domestic coal-based resource materials. Basic and applied science research projects were conducted at national laboratories, small business organizations, and numerous universities, which led in 2016 to the design, construction, and operation of bench- and small pilot-scale facilities, and in 2018 to the production of small quantities (e.g., approximately 100 g/day) of greater than 90% (900,000 parts per million [ppm]) high-purity, mixed rare earth oxides (MREOs) using conventional physical beneficiation and chemical (hydrometallurgical) separation processes.

2019 to 2024 – Expansion to include recovery of both REEs and critical minerals from coal-based resources

To comply with Executive Order 13817, NETL's program expanded its technology development effort in 2019 to include the recovery of critical minerals from coal-based resources. As a result, in 2020, NETL's program required existing domestic small pilot-scale facilities to co-produce critical minerals in addition to producing REEs. In 2021 NETL initiated basinal coalition efforts to address realization of the full economic potential value of U.S. natural resources for producing REEs, critical minerals, and high-value, nonfuel, carbon-based products. The program is also holistically assessing upstream mining of resources and physical separation (e.g., beneficiation); midstream processing, separation, recovery; purification of critical and high-value materials; and, ultimately, onshore downstream manufacturing that incorporates these materials into commodity or national defense products. In 2022, the program was renamed to Critical Minerals and Materials, encompassing research on both REEs and critical minerals, collectively referred to as critical minerals and materials (CMM). Currently, state-of-the-art, conventional separation process system concepts are being assessed for near-future production of 1–3 tonnes/day of high-purity MREOs from coal-based resources in engineering prototype facilities.

Additional information regarding the history of the Critical Minerals and Materials Program is available at [REE Project Information - Historical Perspective | netl.doe.gov].

4 Executive Order 13817, A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals, December 20, 2017. List of Critical Minerals posted in Federal Register/Vol. 83, No. 97/Friday, May 18, 2018/Notices.

5 Executive Order 13953, Threat to the Domestic Supply Chain From Reliance on Critical Minerals From Foreign Adversaries and Supporting the Domestic Mining and Processing Industries, September 30, 2020.

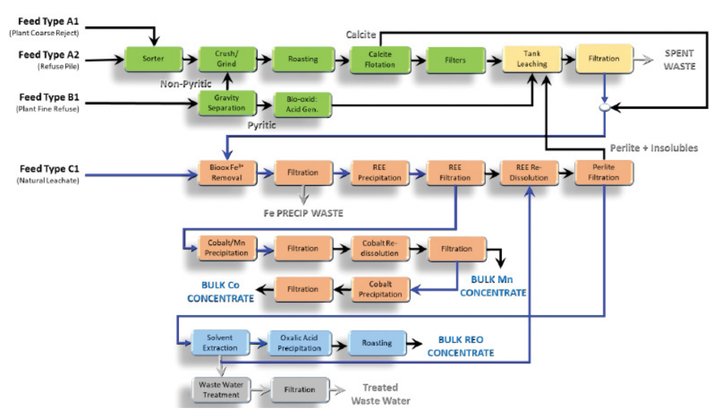
CONVENTIONAL RARE EARTH ELEMENT SEPARATION SYSTEMS

Demonstration of Scaled-Production of Rare Earth Oxides and Critical Materials from U.S. Coal-Based Sources

Performer	**University of Kentucky**
Award Number	FE0031827
Project Duration	10/01/2019 – 12/31/2022
Total Project Value	$ 6,250,000
Collaborators	Virginia Polytechnic Institute and State University; University of Utah; Mineral Separation Technologies, LLC; Alliance Resource Partners; Kentucky River Properties, LLC
Technology Area	Process Systems – Small Pilot-Scale Facility

University of Kentucky extended the activities of the existing rare earth elements (REE) small pilot-scale plant to integrate and test new technologies and circuits to significantly reduce the cost of producing mixed rare earth oxides (MREO), cobalt, and manganese. Concentrate production was increased from between 10 and 100 grams/day to about 200 grams/day. To significantly reduce the primary cost of producing the concentrates, naturally occurring coal pyrite was recovered and used in bioreactors to produce the acid needed for leaching. To assess the technical and economic potential of extracting REE from coal waste, a ¼-ton-per-hour modular small pilot plant was designed, constructed, and tested as part of an ongoing project funded by DOE. Although the small plant was successful in recovering REE and producing MREO having a purity level greater than 90 wt%, several economic barriers were encountered that required more detailed evaluations and modification of the process circuitry. A reduction in the chemical costs per kilogram of REO recovered was needed for the process to be economically viable for a typical coal source.

This project consisted of a team of researchers from the University of Kentucky, University of Utah, and Virginia Tech. Alliance Coal was the host and provider of operational support for the pilot plant as well as the necessary quantity of qualified feedstock. Kentucky River Properties, LLC, collected and transported several tons of qualified feedstock to the pilot plant location. Mineral Separation Technologies provided a dual X-ray transmission sorter for separation of the feedstock into materials that contain potentially high concentrations of REE. The information garnered from simultaneous assessment of process cost guided process development and circuit design to enhance performance success and the potential for commercialization. At the end of the project, a pathway was established for the production of high-purity MREO (greater than 90 wt%) and other critical material concentrates (greater than 50 wt%) from bituminous coal resources in an environmentally friendly manner at a production rate of around 0.2 kg daily.



Integrated process flowsheet showing the addition of innovative technologies implemented to enhance the economic extraction of REE, Sc, Co and Mn from pre-combustion bituminous coal-based sources.

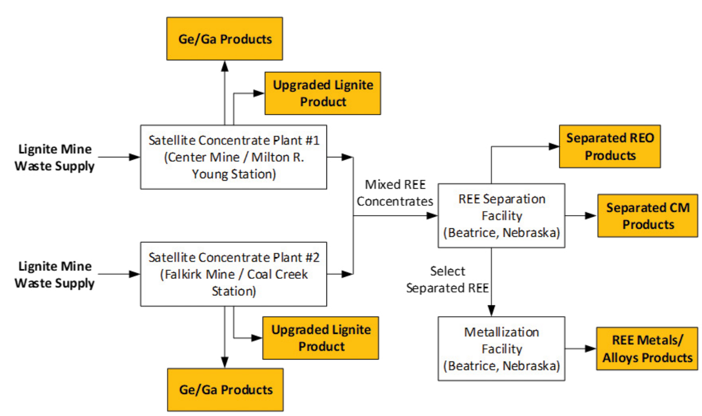
Bipartisan Infrastructure Law (BIL): Recovery and Refining of Rare Earth Elements from Lignite Mine Wastes

Performer	**University of North Dakota**
Award Number	FE0032295
Project Duration	08/01/2023 - 04/30/2025
Total Project Value	$ 9,999,999
Collaborators	AmeriCarbon, LLC, Barr Engineering, BNI Energy, Dennis James Consulting, LLC, Envergex, LLC, Golder Associates, Inc., Lattice Materials, LLC, Microbeam Technologies, Inc., Minnkota Power Cooperative, Inc., MLJ Consulting, LLC, North American Coal Corporation, North Dakota State Building and Construction Trades Council, Odney, Inc., Rainbow Energy Center, LLC, Rare Earth Salts
Technology Area	Production Facilities

The College of Engineering & Mines at the University of North Dakota, in collaboration with a comprehensive team of technical, business and host-site partners and with funding support from the North Dakota Industrial Commission, will build on prior technology development to complete a front-end engineering and design (FEED) study and business plan to recover and refine rare earth elements (REE) and critical minerals (CM) from North Dakota lignite mine wastes. The end-of-project goal is to have an investment-quality project and a committed team that is ready to execute the construction and operation of the REE Demonstration Facility in Phase II.

To achieve this goal, the objectives of the Phase I project are as follows: (1) quantify the proposed project's job benefits and evaluate how to attract, train, and retain a qualified workforce; (2) identify specific diversity, equity, inclusion, and accessibility goals, targeted outcomes, and implementation strategies; (3) ensure that the project will provide meaningful benefits to disadvantaged communities and will not result in an increased burden to disadvantaged communities; (4) identify and implement methods for project stakeholder engagement; (5) develop all required permit applications and other regulatory approvals, including providing information for National Environmental Policy Act review, by the end of Phase I; (6) develop an Association for the Advancement of Cost Engineering (AACE) Class 3 FEED study for the REE Demonstration Facility and satellite sites to advance the project to investment quality; (7) perform limited research and development to de-risk certain technology subsystems and ensure the overall process functions smoothly in the integrated circuits; and (8) develop the Phase II business and financing plans to formalize the overall commercial structure and secure construction financing.

The Bipartisan Infrastructure Law (BIL) will invest appropriations of $156 million for the design, construction, and operation of a Rare Earth Element Demonstration Facility that demonstrates the extraction, separation and refining from unconventional feedstock materials to high purity individual or binary rare earth metals and/or critical minerals and materials (CMM). The projects funded under DE-FOA-0002618 support BIL sections 40205 and 41003(b) and the broader government-wide approach to upgrading and modernizing infrastructure, including by strengthening critical domestic manufacturing and supply chains to maximize the benefits of the clean energy transition as the nation works to curb the climate crisis, empower workers, and advance environmental justice.



Proposed REE demonstration facility and satellite sites.

Rare Earth Element Extraction and Concentration at Pilot-Scale from North Dakota Coal-Related Feedstocks

Performer	University of North Dakota
Award Number	FE0031835
Project Duration	10/01/2019 – 06/30/2024
Total Project Value	$ 7,158,555
Collaborators	Barr Engineering; BNI Energy; Great River Energy; Industrial Commission of North Dakota - Lignite Energy Council; Microbeam Technologies; Minnkota Power; North American Coal Corporation; North Dakota Geological Survey; North Dakota Industrial Commission; Rare Earth Salts
Technology Area	Process Systems – Small Pilot-Scale Facility

The University of North Dakota (UND) is demonstrating at small pilot scale a high-performance, economically viable and environmentally benign technology to recover rare earth elements (REE) from North Dakota (ND) lignite coal feedstocks. To achieve this goal, UND is:

- Designing and constructing a small pilot-scale system for continuous REE extraction from ND coal feedstocks capable of using a minimum 0.5 ton per hour feed rate of physically beneficiated lignite coal.
- Obtaining approximately 300 tons of ND lignite containing greater than 300 ppm REE to provide adequate material for shakedown and continuous testing in the small pilot-scale demonstration facility.
- Conducting initial parametric testing of a sample of the ND lignite at bench scale to cost-effectively identify optimal operating conditions and aid in the design of the small pilot-scale system.
- Commissioning the small pilot facility using selected high-REE-containing coals from various regions in ND.
- Conducting continuous small pilot-scale testing under optimal conditions for REE extraction and concentration using at least 100 tons of ND lignite that contains greater than 300 ppm REE.
- Confirming compatibility of REE concentrate generated during small pilot-scale testing with commercial-scale REE refining.
- Using results from the small pilot-scale testing to conduct a techno-economic analysis (TEA) and preliminary front end engineering design (pre-FEED) study on a potential commercial facility where an economic feasibility study and workforce assessment will be performed.
- Working with industry partners to develop a technology roadmap and commercial deployment plan.

UND's efforts will provide information on availability of the proposed feedstock and environmental impacts; process flow diagram(s); product yield and concentration; and estimated system costs.

Coarse (left) and fines (right) coal piles extracted from Freedom Mine.

Bipartisan Infrastructure Law (BIL): Acid Mine Drainage and Rare Earth Elements (AMDREE): Integrated Treatment of Acid Mine Drainage and Rare Earth Production

Performer	**West Virginia University**
Award Number	FE0032296
Project Duration	08/01/2023 - 04/30/2025
Total Project Value	$ 11,704,182
Collaborators	Virginia Polytechnic Institute and State University
Technology Area	Production Facilities

The objective of this project is to complete the front-end engineering design and pre-construction planning activities for a first-of-a-kind demonstration facility capable of producing rare earth elements (REE) and select critical minerals and materials (CMM) from domestic acid mine drainage and mineral tailings feedstocks. The facility will be designed to produce 1 to 3 metric tons per day of mixed rare earth oxides that will be separated into individual and binary REE and CMM components at a single site. The project team will develop a cost estimate according to Association for the Advancement of Cost Engineering Class 3 guidelines. This project could incentivize the treatment of hundreds of legacy acid mine drainage discharges, allow streams to recover productivity, and produce a robust and steady supply of high value REE and CMM for domestic industries.

The Bipartisan Infrastructure Law (BIL) will invest appropriations of $156 million for the design, construction, and operation of a Rare Earth Element Demonstration Facility that demonstrates the extraction, separation and refining from unconventional feedstock materials to high purity individual or binary rare earth metals and/or critical minerals and materials. The projects funded under DE-FOA-0002618 support BIL sections 40205 and 41003(b) and the broader government-wide approach to upgrading and modernizing infrastructure, including by strengthening critical domestic manufacturing and supply chains to maximize the benefits of the clean energy transition as the nation works to curb the climate crisis, empower workers, and advance environmental justice.

Recent Mixed Rare Earth Oxide (MREO) production at the A34 Facility which is operated jointly with the West Virginia Department of Environmental Protection. The A34 plant treats acid mine drainage for discharge to the headwaters of the Potomac River and produces these Light and Heavy MREO concentrates.

Development and Testing of an Integrated Acid Mine Drainage (AMD) Treatment and Rare Earth/Critical Mineral Plant

Performer	**West Virginia University Research Corporation (WVURC)**
Award Number	FE0031834
Project Duration	10/01/2019 – 09/30/2023
Total Project Value	$ 6,886,791
Collaborators	Rockwell Automation; Virginia Polytechnic Institute and State University
Technology Area	Process Systems – Small Pilot-Scale Facility

The primary objective of this project is to design, construct, and test—in conjunction with their partners West Virginia Department of Environmental Protection and Rockwell Automation, Inc.—a pilot-scale continuous, integrated process for simultaneously and efficiently treating up to 1,000 gpm of acid mine drainage (AMD) while producing an enriched REE/CM (Rare Earth Elements/Critical Minerals) concentrate. WVURC will carry out the objectives in two phases. The first phase will focus on the engineering design, construction, and assembly of the pilot-scale process equipment to be used in the project. To support these development efforts, WVURC will construct and test a small-scale, fully-continuous test unit to emulate the performance of the upstream concentrator. This test unit will allow rapid optimization of various operational variables and limit the need for extensive testing at the larger scale. During the second phase of work, the integrated pilot plant will be operated on a continuous basis to validate process performance and refine process cost estimates. During both phases, other efforts will focus on critical support tasks including technical and environmental systems analysis.

WVURC has identified that AMD from sulfidic coal and other ore bodies is an attractive source of REE/CM since it relies on natural processes to create a concentrated, easily extracted feedstock. Further, WVURC has demonstrated that this process is environmentally beneficial since it would incentivize treatment of AMD and produces insignificant naturally occurring radioactive material (NORM) or other noxious wastes. It is expected that, in the Appalachian States alone, more than 50 new, large AMD treatment plants will be installed in the next 10 years. In addition to addressing one of the region's largest sources of stream pollution, this new type of AMD treatment plant will generate a steady supply of REE/CM, a strategically important and valuable product stream. If successful, this plant will generate about 1,000 tons per year of REE/CM oxides with an estimated contained value of $237/kg. It will pioneer a new means of treating AMD in a financially sustainable way by providing the operator, the West Virginia Department of Environmental Protection, a revenue stream that will sustain a large portion, if not all, of the required operating costs. This facility has the potential to become the AMD treatment plant of the future with application across all sulfide mining properties both domestically and internationally.

Internal view of the pilot-scale facility, which will simultaneously treat acid mine drainage and produce an enriched rare earth element and critical mineral concentrate.

Rare Earth Element (REE) Extraction from Powder River Basin (PRB) Coal Byproducts

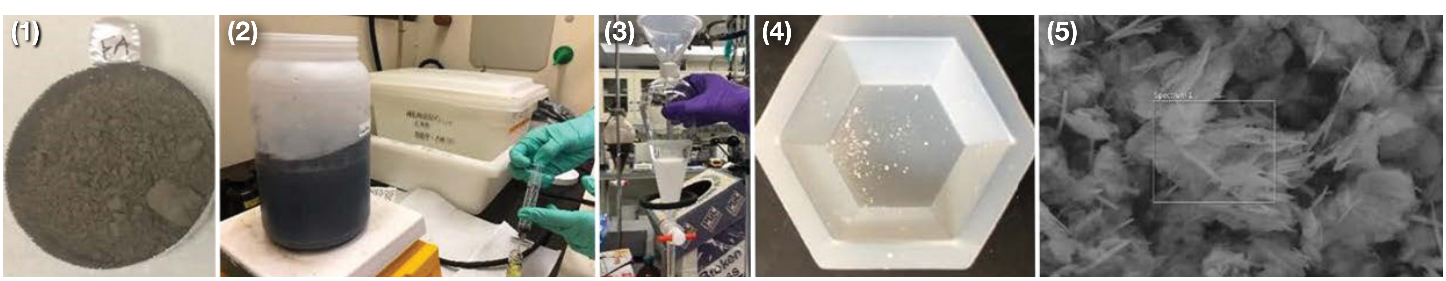
Performer	**National Energy Technology Laboratory**
Award Number	TCF-20-21358
Project Duration	12/02/2020–12/01/2023
Total Project Value	$ 1,620,000
Collaborators	University of Wyoming; Campbell County, WY; Gillette, WY; Energy Capital Economic Development
Technology Area	Enabling Technologies

The project will mature a promising process to produce rare earth elements (REE) from a coal-related feedstock—fly ash created from the combustion of Powder River Basin (PRB) coal—by partnering with leading academic and industrial entities in Wyoming. The project will culminate in the creation and start-up of a pilot-scale production facility to demonstrate the process performance and economics, reducing the risk to the construction of a full-scale facility.

The project objectives are to (1) identify the most promising feedstock(s) in the PRB for the extraction of REE and critical minerals (CM), (2) demonstrate the efficacy of extracting REE and CM in an economical manner, and (3) demonstrate the feasibility of up-scaling NETL extraction technologies to a pilot scale in the PRB. In order to meet these objectives, the team will leverage regional geologic and industrial knowledge from the University of Wyoming consortium with extraction chemistry capabilities and intellectual property from NETL to demonstrate the commercial viability of the REE extraction process.

Moreover, patented NETL sorbent and membrane technologies will be leveraged for incorporation into downstream REE oxide production from each feedstock. The project will accelerate the use of PRB coal-related wastes as a critical mineral resource.

There is currently a gap in the production of domestic REE ore or concentrates, forcing REE refiners/concentrators to seek feedstocks from overseas. This technology will fill that gap by providing a REE concentrate from a domestic feedstock—coal refuse or coal fly ash—which is a byproduct of other industrial activities. The use of an industrial byproduct as a feedstock has the potential to make power generation from Wyoming coal more competitive and the presence of two revenue streams—electricity and REE concentrate—limits the impact of price shifts in either market. The focus on waste materials from PRB coal is notable because it represents 40% of U.S. coal production and ultimately could be used to meet a significant portion of U.S. demand for REE.



Rare earth elements and yttrium (REY) recovery processing chain of the tested PRB fly ash. Photos from left to right display: (1) PRB fly ash as received, (2) large laboratory scale step leaching process, (3) organic solvent extraction for REY purification; (4) final oxalate precipitant collected, (5) scanning electron microscope image of oxalate product containing 30 wt% REY.

NOVEL REE SEPARATION AND ADVANCED SENSOR DEVELOPMENT

— FIELD WORK PROPOSAL (FWP) PROJECTS —

Machine Learning-aided Multi-physics Identification and Characterization of REE-CM Hot Zones in Mine Tailings for Economic Recovery

Performer	**Lawrence Berkeley National Laboratory (LBNL)**
Award Number	FWP-FP00016201
Project Duration	01/01/2023 – 12/31/2024
Total Project Value	$ 1,200,000
Technology Area	REE Detection Systems

Characterization of rare earth elements and critical minerals (REE/CM) in unconventional and secondary sources is a complex task that needs to overcome the challenges of detecting low and variable concentrations and the uniqueness of every source material deposit in terms of composition, host material, and disposal environment. As in traditional mineral prospecting, delineation of REE/CM "hot zones" is critical for assessing the economic viability of these sources. Here, hot zone is defined as a spatially delineated volume of high REE/CM concentrations within the tailing deposits. The project will develop and field demonstrate a machine learning-aided multi-physics approach for rapid identification and characterization of REE/CM hot zones in mine tailings with a focus on coal and sulfide mine tailings or other processing or utilization byproducts, such as fly ash and refuse deposits.

Research, development, design, and deployment under the award will create new methodologies, tools, and technologies required for identifying and assessing the quality (e.g., composition and impurities) and quantity of critical minerals and carbon ore available for sustainable commercial production from a variety of unconventional and secondary resources. This research could also be leveraged to potentially form a multi-laboratory effort to collaborate on improving characterization, resource assessment, and recovery efficiency of REE/CM in unconventional and secondary resources that would enable real-time sensing/quantification of REE/CM on the subsurface; predictive capabilities to characterize and assess the location, mineralogy, and quantity of REE-CMs more effectively and efficiently; and forecasting of resource potential (i.e., resource reserves).

The project will develop sensor technologies to quantify CM in coal and coal-related materials and REE/CM in other unconventional and secondary sources, or energy-related streams, including the interplay between characterization technology on core, outcrop, and regional scale, thereby leading to improved recognition of REE/CM concentrations in feedstocks.

Mine tailings.

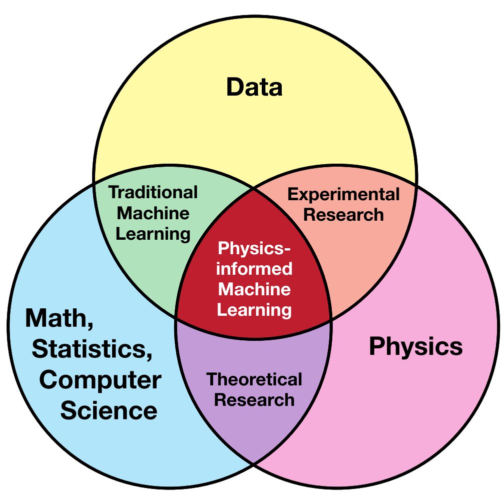
A Machine Learning Screening Tool for Rare Earth Elements and Critical Minerals at the Mine Scale

Performer	**Los Alamos National Laboratory (LANL)**
Award Number	FWP-LANL-AE-1263-1711
Project Duration	03/01/2023 – 02/28/2025
Total Project Value	$ 1,200,000
Collaborator	University of Wyoming
Technology Area	REE Detection Systems

The objective is to develop a mine-scale tool that can be used to screen mines and other geologic deposits for potential viability as rare earth element (REE) and critical mineral (CM) mines. Machine learning techniques will be used in combination with existing and newly collected data from the Wyodak Mine to develop this screening tool. While developed with data from Wyodak, the tool will be site-agnostic and enable users to identify whether or not a mine has economic potential for mining REE/CM and to identify regions within the mine with a high probability of economic viability.

Research, development, design, and deployment under the award will create new methodologies, tools, and technologies required for identifying and assessing the quality (e.g., composition and impurities) and quantity of critical minerals and carbon ore available for sustainable commercial production from a variety of unconventional and secondary resources. This research could also be leveraged to potentially form a multi-laboratory effort to collaborate on improving characterization, resource assessment, and recovery efficiency of REE/CM in unconventional and secondary resources that would enable: real-time sensing/quantification of REE/CM on the subsurface; predictive capabilities to characterize and assess the location, mineralogy, and quantity of REE/CMs more effectively and efficiently; and forecasting of resource potential (i.e., resource reserves).

The project will provide insight into characterization approaches and methodologies that would provide advanced assessment of the quantity, location (spatial distribution), form (mineralogy), extractability, and recovery of unconventional and secondary REE/CM, thereby leading to improved characterization of REE/CM feedstocks.



Physics-informed Machine learning inputs.

Minerals Sustainability (Resource Characterization)

Performer	**National Energy Technology Laboratory – Research and Innovation Center**
Award Number	FWP-1022420
Project Duration	04/01/2018 – 03/31/2024
Total Project Value	$ 20,857,501
Technology Area	Enabling Technologies, Separation Technologies, and Process Systems

The work in this research focus area develops and validates a geo-data science-driven approach for systematically assessing unconventional rare earth element and critical materials (REE/CM) occurrences in sedimentary strata to identify targets of predicted higher prospectivity. This includes the development of predictive models and identification of key data and knowledge gaps that hinder resource predictions. This focus area also plugs these identified gaps in knowledge by targeted sample collection and characterization of geologic samples from archived or recently collected drill cores from domestic sedimentary strata. These efforts harmonize geological, geochemical, and geospatial datasets from DOE, USGS, state agencies, and other public sources to assess and validate if REE/CM occur in adequate concentrations and volumes to support commercial extraction in priority U.S. basins. A new task in this focus area will develop a national REE/CM database and virtual online dashboard for rapid and efficient assessment of REE/CM sedimentary resources. Finally, a second new task in this focus area will begin to collect, curate, and build a database of lithium (Li) brine chemistry and associated attribute data (production volumes, etc.) for major U.S. shale plays.

This effort will be beneficial, as CM occur in small quantities in coal and coal byproducts (as compared to traditional ore bodies) and currently processes are being explored to economically recover CM/REE from coal and coal by-products. Furthermore, technologies that currently exist for the extraction of REE from other resources use large amounts of aggressive and toxic chemicals and are not suitable for deployment in the United States. Current methods for acid mine drainage (AMD) solids only extract REE as end-products, whereas cobalt (Co), nickel (Ni), zinc (Zn), and Li are detected at very high concentrations and values in existing AMD solids.

This research is maximizing all REE and CM value from the AMD solids via cost-effective, characterization-informed, and environmentally friendly sequential leaching. An application of this approach would be the use of advanced characterization techniques on acid mine drainage solids to inform binding conditions of CM, including REE, Co, Ni, Zn, and Li, in these materials. The knowledge gained from characterization will be further developed into innovative and informed sequential extractions targeting the major REE and CM-hosting solid fractions for efficient and economical REE/CM recovery. This effort will provide useful information on geographic trends in resource availability in public basins that will guide further research in the valorization of lithium resources in oil and gas wastewater.

Minerals Sustainability (Emerging Resources)

Performer	**National Energy Technology Laboratory – Research and Innovation Center**
Award Number	FWP-1022420
Project Duration	04/01/2018 – 03/31/2024
Total Project Value	$ 20,857,501
Technology Area	Enabling Technologies, Separation Technologies, and Process Systems

Unconventional critical mineral resources are high-potential targets for industrial-scale resource recovery, but in many cases the modes of occurrence and methods of enrichment are poorly understood. The research in this portfolio includes the core R&D related to understanding unconventional critical mineral resources, their potential recovery, and techniques that can help these unconventional resources emerge as viable industrial-scale sources of critical minerals. Advanced characterization methods are used to understand how critical minerals are bound in materials such as coal ash and acid mine drainage solids to give clues to the most environmentally benign methods of extraction and to help understand the opportunities for improvement of existing processes. This focus area is developing a biological process to facilitate release of critical materials (CM) from acid mine drainage (AMD) treatment solids. It is also maturing and optimizing a heap leach process for REE extraction from clays and legacy coal wastes. A new task this year is identifying technical barriers and developing in-situ methods for REE and CM recovery from non-traditional subsurface resources including shales and coals.

AMD results from the interaction of groundwater with abandoned coal mines, producing waters that require treatment to minimize environmental impacts. This waste stream is a potentially valuable resource for REE and CM recovery. The Appalachian basin AMD alone could meet up to 30% of the U.S. annual REO demand in 2018. Even though AMD is a valuable domestic source of CM, it is currently being treated as a costly waste management problem, and the biotechnology has not yet been developed to economically extract CM from these resources.

Current treatment processes of AMD already concentrate CM into solid phases that could be released and recovered. AMD is treated by modifying pH and redox conditions to neutralize acidity and decrease the solubility of dissolved metals. The precipitation of these metals generates material often referred to as AMD treatment solids that must be managed at significant cost to treatment system operators. These AMD treatment solids are typically landfilled or pumped into abandoned mines for disposal. However, many of these solids are MnO_X/FeO_X/AlO_X-laden materials that sequester CM to concentrations approaching those in ores. Microorganisms that naturally reside in the treatment solids may already have the capability to reduce the treatment's solids, and enrichment of these microorganisms would release trapped CM in a solution called a pregnant leachate solution (PLS). This would create a value stream from these waste products that would improve the economics of AMD treatment while also addressing the need for a domestic source of CM.

Minerals Sustainability (Emerging Technologies)

Performer	**National Energy Technology Laboratory – Research and Innovation Center**
Award Number	FWP-1022420
Project Duration	04/01/2018 – 03/31/2024
Total Project Value	$ 20,857,501
Technology Area	Enabling Technologies, Separation Technologies, and Process Systems

The emerging technologies under study operate at various points in the CM supply chain and are considered important enabling technologies because they have the potential to dramatically improve the viability of existing processes or to make new markets for materials. One important effort at NETL is the development of high-volume materials technologies based on super-abundant mischmetal components, cerium (Ce) and lanthanum (La). NETL research focuses on development in two areas: high-strength steels and environmental barrier coatings. Another technology seeks to develop improved sorbents for the extraction of CM from produced waters. A novel sorbent is also being developed using hollow fibers to improve high-volumetric rate applications. Two projects are also included in this focus area that are intended to take separate approaches to improving the real-time measurements of critical minerals in solutions. One focuses on fiber optic sensors and the other uses laser-induced breakdown spectroscopy (LIBS) designed for down-hole testing in geologic environments. Two projects seek to develop direct lithium (Li) extraction methods from produced waters. One is developing a low-cost Li sorbent synthesized from acid mine drainage (AMD) treatment wastes to generate robust Li concentrate from different oil and gas produced waters and another uses a non-sorbent-based direct lithium extraction process dependent on carbonation.

La and Ce are the most abundant REE in both conventional domestic sources (e.g., monazite and bastnasite minerals) and unconventional domestic sources (e.g., legacy coal mining and related waste streams). Despite a relatively high demand for these elements, they are currently considered low-value byproducts of the extraction of more valuable REEs. This is due to the so-called REE balance problem, where significant extraction of co-occurring REEs, such as Nd, produces an oversupply of La and Ce and decreases their value. Meanwhile, current materials which rely on purified versions of expensive and scarce REE-oxides such as ytterbium oxide (Yb_2O_3) as precursors, may exhibit similar or better performance using mixtures of REE-oxides that are readily produced from unconventional domestic sources.

Developing new materials which use domestically abundant REE at large rates will address the REE balance problem and increase the value of domestically abundant REE. Using mixed REE oxide precursors derived from unconventional sources in place of purified REE-oxides without sacrificing material performance will save on costly purification steps. Both strategies will improve the economics of domestic REE production

Minerals Sustainability (Systems Analyses)

Performer	**National Energy Technology Laboratory – Research and Innovation Center**
Award Number	FWP-1022420
Project Duration	04/01/2018 – 03/31/2024
Total Project Value	$ 20,857,501
Technology Area	Enabling Technologies, Separation Technologies, and Process Systems

The focus of the task is to understand the cost, performance, and environmental footprint of critical materials (CM) concentration and separation from non-conventional feedstocks, identify cost and performance R&D needs in the extraction of CM from non-conventional feedstocks, understand the CM supply chain and current markets for existing products, and evaluate the economic benefits of in-house transformational processes within the CM supply chain. These efforts focus on life cycle analysis baseline studies for critical minerals and the development of an embedded demand database and the data and principles behind CM process flowsheet optimization calculations that facilitate cost and environmental performance optimization.

Several R&D challenges exist for the development of this independent baseline analysis. Currently there is no global industrial precedence for recovering CM from a non-traditional feedstock. This makes it challenging to collect cost, performance, and environmental data for complete CM processing systems, but that will still be possible since all the processes necessary to recover CM from these sources are commercially deployed in other industries. The cost and performance data will have to be collected for each individual process from a representative industry and adjusted to fit the proposed systems and scales. Environmental performance data is also limited for the extraction and processing of CM. Foundational environmental characterization modeling will be essential to ensuring environmentally responsible minerals production in the United States.

Knowledge and experience with TEA, baseline development, market analysis, and environmental assessments will be used to inform in-house research and evaluate externally proposed projects at the request of the NETL CM Program and the Technology Development Center (TDC), while developing independent baseline analyses to recover CM from non-traditional feedstocks. These independent analyses will be paramount in identifying future R&D needs to advance the economic recovery of CM.

BIL - Process Optimization and Modeling for Minerals Sustainability (PrOMMiS)

Performer	National Energy Technology Laboratory – Research and Innovation Center
Award Number	FWP-1025017
Project Duration	01/01/2023 – 12/31/2024
Total Project Value	$ 2,055,000
Technology Area	Enabling Technologies

The U.S. Department of Energy's Process Optimization and Modeling for Minerals Sustainability (PrOMMiS) Initiative seeks to transform the national rare earth elements and critical minerals (REE/CM) landscape to meet the three enduring strategic objectives of the Department of Energy (DOE): security, economic competitiveness, and environmental responsibility. PrOMMiS will be the premier resource for accelerating the identification, design, scale-up, and integration of innovative REE/CM processes through successful leveraging of NETL's Institute for the Design of Advanced Energy Systems (IDAES) advanced system modeling, optimization, and analysis framework with expertise from existing DOE investment in REE/CM technologies. PrOMMiS will work directly with industry partners to accelerate the scale-up of novel REE/CM technologies by de-risking the development and deployment of commercial-scale processes and maximizing learning throughout the development cycle.

Building on the capabilities developed in IDAES and the Carbon Capture Simulation Initiative (CCSI), PrOMMiS will utilize and deploy next-generation computational tools for rapid design, optimization, scale-up, and integration of REE/CM processes. Working closely with external partners, these tools will be used to accelerate the development and scale-up of new, innovative technologies for recovery and processing of REE/CM from a range of feedstocks, including raw sources, waste streams, and recycling end-of-life-products.

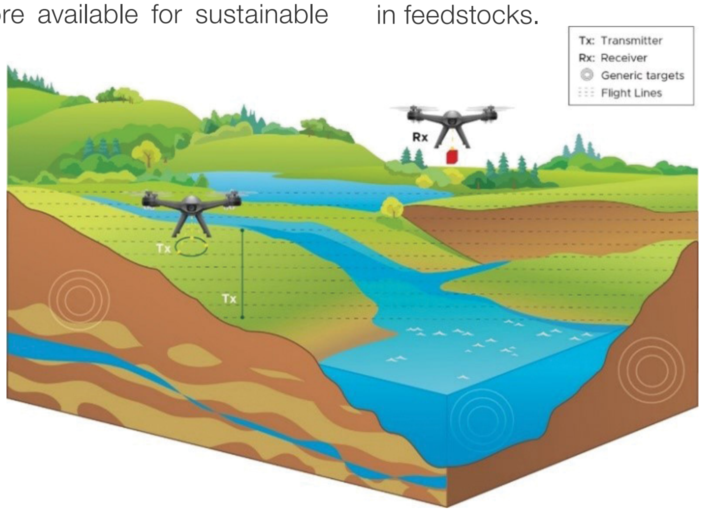
Drone-Based Geophysical Surveying and Real-Time AI/ML Analysis for Sustainable Production of Critical Minerals

Performer	**Pacific Northwest National Laboratory (PNNL)**
Award Number	FWP-81034
Project Duration	02/09/2023 – 02/08/2025
Total Project Value	$ 1,200,000
Technology Area	REE Detection Systems

Pacific Northwest National Laboratory (PNNL) will develop and demonstrate drone-based geophysical and remote-sensing technologies to quantify critical minerals (CM) in coal, coal related, unconventional and secondary sources or energy related waste streams. Drone-based geophysical surveys and remote sensing combined with artificial intelligence/machine learning (AI/ML) analytics for real-time integration and analytics has potential to transform characterization and monitoring of CM from conventional and secondary resources. The sensor technologies, modeling, and data analysis capabilities developed would be agnostic with respect to drone platform and, in principle, could be deployed on ground-based robotic mining or excavation equipment as well.

Research, development, design, and deployment (RDD&D) under the award will create new methodologies, tools, and technologies required for identifying and assessing the quality (e.g., composition and impurities) and quantities of critical minerals and carbon ore available for sustainable commercial production from a variety of unconventional and secondary resources. This research could also be leveraged to potentially form a multi-laboratory effort to collaborate on improving characterization, resource assessment, and recovery efficiency of rare earth elements and critical minerals (REE/CM) in unconventional and secondary resources that would enable real-time sensing/quantification of REE/CM on the subsurface; predictive capabilities to characterize and assess the location, mineralogy, and quantity of REE/CMs more effectively and efficiently; and forecasting of resource potential (i.e., resource reserves).

The project will develop sensor technologies to quantify CM in coal and coal-related materials and REE/CM in other unconventional and secondary sources, or energy-related streams, including the interplay between characterization technology on core, outcrop, and regional scale, thereby leading to improved recognition of REE/CM concentrations in feedstocks.



Schematic diagram illustrating both the fully airborne geometry with drone-based transmitter (Tx) and drone-based receiver(s) (Rx), and the semi-airborne geometry with a powerful ground-based transmitter and drone-based receiver(s).

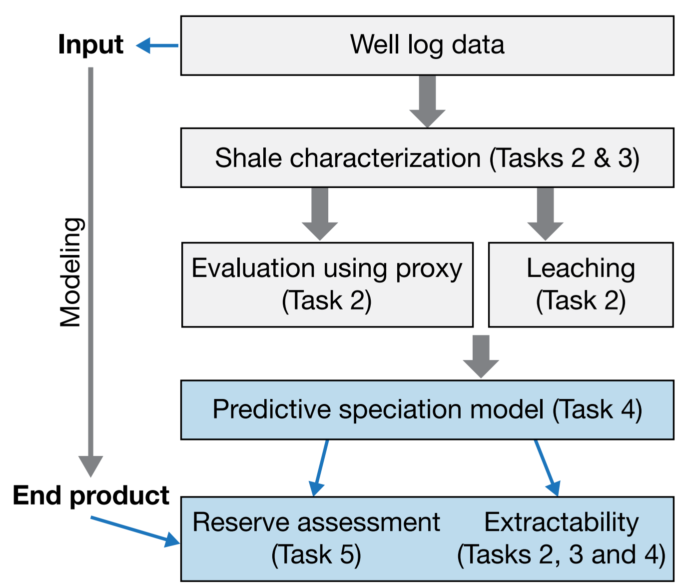
Resource Assessment of Unconventional Oil & Gas Shale for Critical Minerals Recovery

Performer	**Sandia National Laboratories**
Award Number	FWP-23-025668
Project Duration	02/15/2023 – 02/14/2025
Total Project Value	$ 1,200,000
Collaborator	National Energy Technology Laboratory
Technology Area	Enabling Technologies

The goal of this project is to assess the extractability of rare earth elements (REE) and critical minerals (CM), from major oil and shale gas formations across the United States. Specifically, this effort will assess the in-situ extractability of REE and CM using a newly developed combination of supercritical carbon dioxide (sCO_2), water, and chelators such as citric acid. Moreover, this work will establish the technical basis and predictive capabilities to characterize and assess the mineralogy and quantity of REE and CM in shale formations more effectively and efficiently. The predictive model to be developed is expected to find use in forecasting of resource potential (i.e., resource to reserves). If successful, the in-situ leaching concept could be directly integrated into existing oil and gas production and field facilities to obtain REE and CM from shale.

Research, development, design, and deployment (RDD&D) under the award will create new methodologies, tools, and technologies required for identifying and assessing the quality (e.g., composition and impurities) and quantities of critical minerals and carbon ore available for sustainable commercial production from a variety of unconventional and secondary resources.

This research could also be leveraged to form a multi-laboratory effort to collaborate on improving characterization, resource assessment, and recovery efficiency of REE and CM in unconventional and secondary resources that would enable real-time sensing and quantification of REE/CM on the subsurface; predictive capabilities to characterize and assess the location, mineralogy, and quantity of REE/CMs more effectively and efficiently; and forecasting of resource potential (i.e., resource reserves). This project will provide insight into characterization approaches and methodologies that would provide advanced assessment of the quantity, location (spatial distribution), form (mineralogy), extractability, and recovery of unconventional and secondary REE/CM, thereby leading to improved characterization of REE/CM feedstocks.



Integrated modeling and experimental activities for critical metal resource assessment.

Characterization & Extraction of Critical Minerals from Energy Production Waste Streams

Performer	**SLAC National Accelerator Laboratory**
Award Number	FWP-100950
Project Duration	01/01/2023 – 12/31/2024
Total Project Value	$ 500,000
Technology Area	Enabling Technologies

The overall goal of this project is to identify the concentrations and forms of various critical materials (CMs) in unconventional shale waste streams with a focus on rock cuttings from unconventional oil/gas wells. Due to the high volume and wide range of sedimentological facies represented in the rock cuttings created during the drilling process, these are ideal materials to (1) extract critical materials and (2) reduce the environmental impact of the unconventional oil/gas shale process.

Two major objectives will be targeted with this project. Objective 1 is a detailed characterization of the concentration, form, and leachability of CMs plus correlating the various CMs with their respective sedimentological facies both within a specific sedimentary basin and others. Objective 2 is to use findings from Objective 1 to design both universal and targeted extraction protocols for the various CMs in a manner that has a low environmental burden to create a new CM supply chain. These objectives will rely heavily on laboratory-based and synchrotron-based characterization techniques and targeted chemical extractions.

Research, development, design, and deployment (RDD&D) under the award will create new methodologies, tools, and technologies required for identifying and assessing the quality (e.g., composition and impurities) and quantities of critical minerals and carbon ore available for sustainable commercial production from a variety of unconventional and secondary resources.

This research could also be leveraged to potentially form a multi-laboratory effort to collaborate on improving characterization, resource assessment, and recovery efficiency of rare earth elements and critical minerals (REE/CM) in unconventional and secondary resources that would enable real-time sensing and quantification of REE/CM on the subsurface; predictive capabilities to characterize and assess the location, mineralogy, and quantity of REE/CMs more effectively and efficiently; and forecasting of resource potential (i.e., resource reserves). This project will provide insight on characterization approaches and methodologies that would provide advanced assessment of the quantity, location (spatial distribution), form (mineralogy), extractability and recovery of unconventional and secondary REE/CM, thereby leading to improved characterization of REE/CM feedstocks.

Drill cuttings at a well pad in north-central West Virginia, awaiting transport to a landfill.

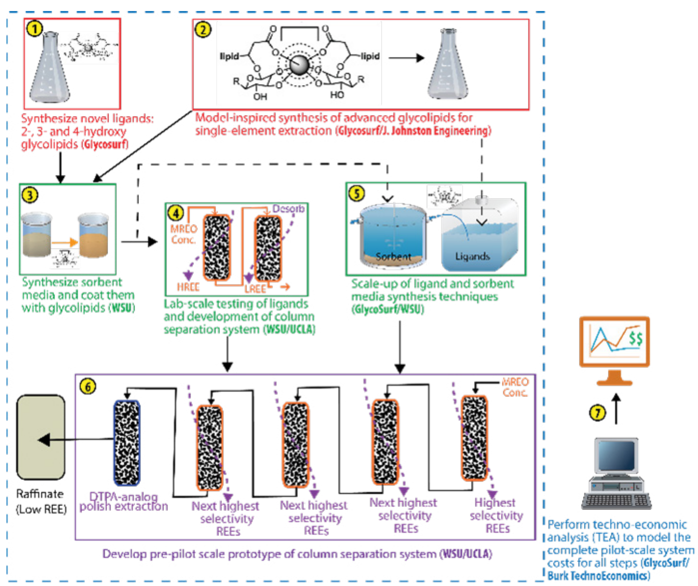
ENABLING TECHNOLOGIES

Development of Ligand-Associated Solid-Liquid Extraction Media System for Separation of High Purity Individual Rare Earth Elements from Coal-based Resources

Performer	**GlycoSurf, LLC**
Award Number	SC0021702
Project Duration	06/28/2021 – 08/21/2024
Total Project Value	$ 1,886,350
Collaborators	University of California - Los Angeles, Wayne State University
Technology Area	Enabling Technologies

Conventional commercial sources of rare earth elements (REE) include bastnäsite ([La, Ce]FCO_3), monazite ([Ce, La, Y, Th]PO_4), and xenotime (YPO_4). However, the processing of these materials to extract and recover the rare earth elements is challenging and very intensive. There are numerous domestic sources of rare earth elements including waste materials such as coal fly ash from which REE could be extracted beneficially. Several physical and chemical methods are typically employed to separate the materials of interest from gangue material, which usually leads to the production of a mixed rare earth element concentrate. The mixed rare earth concentrate is then subjected to an entirely separate process to isolate the individual rare earth elements into high-purity materials for use in commercial applications.

This team will build on its past successes with ligand-associated separation media to develop a new class of sorption media, and a process to separate individual rare earth elements, resulting in individual high purity rare earth oxide (REO) powders. This new class of sorption media will combine two classes of ligands: (1) glycolipids and (2) diethylenetriaminepentaacetic acid (DTPA) analogs, synthesized in-house for fundamental proof-of-concept testing for the proposed novel process to concentrate REEs from coal leachates. The process will also allow for the separation of mixed light REE from the heavy REE, along with separation of these concentrates into individually separated REE materials. The team anticipates that Phase I will result in REO purity of >90% in less than ten processing steps, as opposed to hundreds to thousands of steps for current liquid-liquid separations.



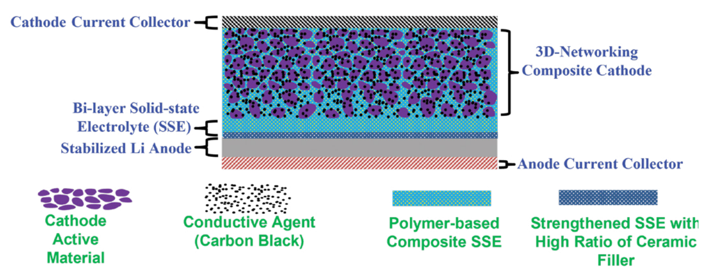
The proposed separation process.

Rare Earth Oxide (REO)-Based High-Voltage, High-Capacity $LiNiPO_4$ as Cathode of High-Safety, High Energy-Density Solid-State Li-Ion Batteries (SSLiBs) for Electric Drive Vehicle Applications

Performer	**Bioenno Tech, LLC**
Award Number	SC0022475
Project Duration	02/14/2022 – 11/13/2022
Total Project Value	$ 200,000
Collaborator	Aegis Technology, Inc.
Technology Area	Enabling Technologies

The objective of this SBIR Phase I project was to design and present a cost-effective manufacturing process for high voltage cathode materials enhanced with rare-earth oxide (REO) doping/co-doping. They are based on two promising high-voltage cathode materials, cobalt (Co)-free olivine compound $LiNiPO_4$ (LNP, 5.1V) and Co-free and Mn-rich spinel $LiNi_{0.5}Mn_{1.5}O_4$ (LNMO, 4.7V), which are needing improvement in stability before their being available and acceptable for commercial applications. It is expected that our proposed enhancement technique would stabilize these structures to enable the potential commercial applications of high voltage cathodes for new-generations of Li-ion batteries (LiBs) for electric-drive vehicles and energy storage systems.

The accomplished Phase I successfully carried out the feasibility investigations, including material design, processing development, and prototype demonstrations, in which the design and synthesis of REO-doped high voltage cathode materials including LNMO and LNP were well demonstrated. A cost effective, scalable solid-state reaction (SSR)-based process was well established and employed to fabricate these REO-doped high voltage cathode materials with good material microstructure (particle size/morphology) and crystalline structure. The REO-doped material samples showed decreased particle sizes and faceting in microstructure and more long-range structural disorder that would benefit the battery performance. The electrochemical characterizations of SSLiB coin cells demonstrated the performance improvement, among which the Ce_2O_3-doped samples showed the best enhancement. A novel class of SSLiBs by integrating the resultant high performance cathode materials and in house developed high performance solid-state electrolyte (SSE), and Li metal anode into a single-layer scale pouch cell has been demonstrated.



Schematic illustration of the proposed solid-state Li-ion batteries.

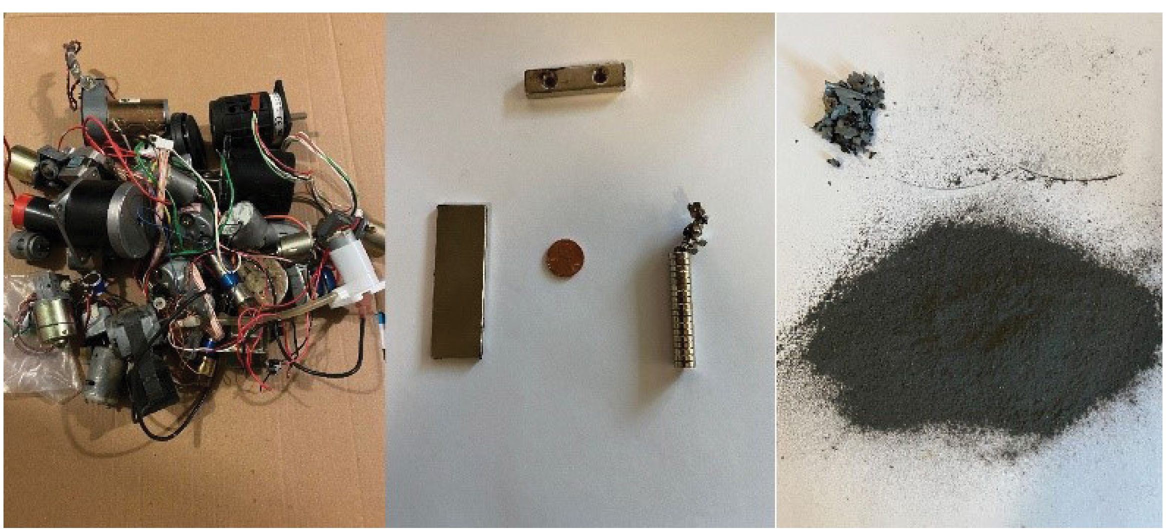
REDUCTION TO METALS

Hydrogen Plasma Reduction of REOs/Salt for REMs Production

Performer	**Polykala Technologies, LLC**
Award Number	SC0021544
Project Duration	02/22/2021 – 04/02/2025
Total Project Value	$ 1,350,000
Collaborators	Savannah River National Laboratory (SRNL); Trimeric Corporation; University of Wyoming
Technology Area	Reduction to Metals

This project will develop a promising and environmentally friendly technology for recycling of the strategic and value-added rare earth metals neodymium (Nd), europium (Eu), yttrium (Y), dysprosium (Dy), samarium (Sm), and cerium (Ce) from post-consumer electronics, electric motors, and waste materials. The process for direct recycling of rare earth magnets and high-purity rare earth metals production will be scaled up and will achieve 50 kg/day production scale by the end of the Phase 2. In addition to scaling up in Phase 2, the team will investigate more efficient reactions by compressing the ingredients to a more compact shape using available metal dies.

America's critical materials and manufacturing supply chains for production of commodity and national defense products no longer reside domestically but are controlled predominantly by offshore markets. Approximately 40% of mined rare earth production is reduced to metals and alloys, including most of Nd, Sm, and Dy, for applications such as neodymium metal for Nd-iron-boron permanent magnets, samarium metal for Sm-cobalt permanent magnets, and lanthanum, Ce, praseodymium, and Nd for rechargeable battery electrodes. This project seeks to continue the expansion of technology beyond production of salable rare earth oxides and/or rare earth salts, through development of advanced processing metallization concepts, to ultimately produce individually separated rare earth metals (REMs) domestically. These REMs would be available for intermediate and/or end-use commercial products or defense equipment.



Left, used electric motors. Middle, used rare earth magnets. Right, recovered/recycled magnetic materials.

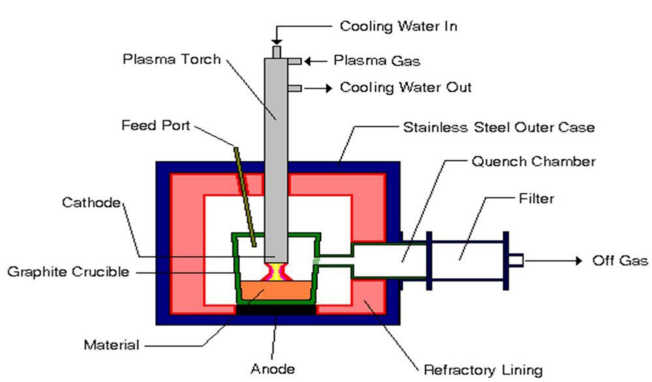
Multi-Sourced Collaboration for the Production and Refining of Rare Earth and Critical Metals

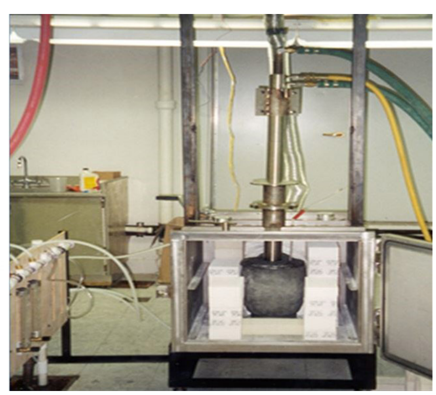
Performer	**University of Kentucky**
Award Number	FE0032119
Project Duration	12/01/2021 – 02/28/2023
Total Project Value	$ 261,398
Collaborators	Alliance Coal; Argonne National Laboratory; MP Materials Corp.; University of Alabama; Virginia Polytechnic Institute and State University
Technology Area	Rare Earth Recovery

This project identified and evaluated advanced refining and metal production technologies capable of extracting high-purity rare earth elements (REE) and critical minerals (CM) and metals from coal-based sources economically and in an environmentally friendly manner.

Previously, the performer successfully designed, constructed, and operated a pilot-scale rare earth processing facility that uses conventional approaches to extract and recover REE. Operational data from this facility have demonstrated the ability to successfully produce rare earth oxide (REO) concentrates at grades exceeding 90% and at production rates of 10 to 100 g/day. The facility is currently being expanded to 110 kg/year. However, this facility does not have the capability to produce individually separated high-purity REE. Through this nine-month effort, the project team delivered a pathway and research plan to apply advanced technologies for individually separated high-purity rare earth and critical minerals production from coal-based sources and reduction to metal that will minimize environmental impact and reduce capital and operating expenses by more than 20% over conventional processes while delivering at a minimum the following rare earths and critical minerals: (REE) Y, Pr, Nd, Gd, Dy of greater than 99.5% purity, and (CM) Co, Mn, Ga, Sr, and Li of greater than 90% purity.

Research, development, and demonstration (RD&D) efforts to create new domestic sources of rare earth elements and other critical minerals have been accelerated with the goal of making our domestic supply chains more resilient. Technology development and optimization of process circuits from recovery of mixed rare earth oxides/mixed rare earth salts (MREO/MRES) and CM from diverse sources, through separation into individual CM or binary high-purity REO/RES, to conversion into rare earth metals (REM) is critical to establishing a resilient domestic supply chain that is not threatened by geopolitical competition.





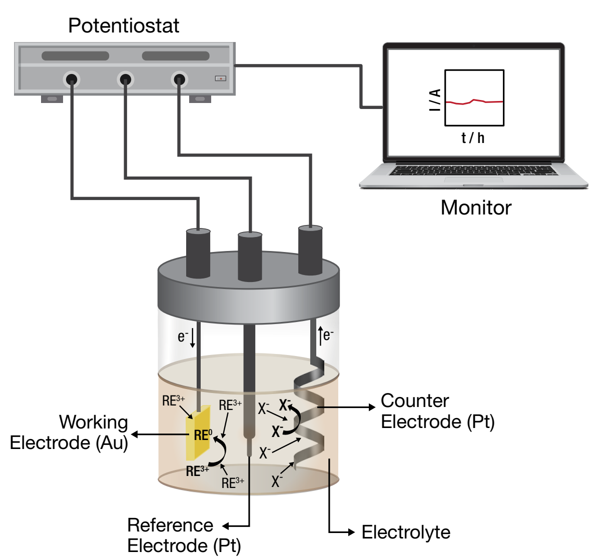
Advanced Thermal Plasma Reactor for REE and CM metal production.

Tunable Electrochemical Pathway for High-Purity Rare Earth Metals (REM) and Critical Minerals (CM)

Performer	**University of North Dakota Energy and Environmental Research Center (UNDEERC)**
Award Number	FE0032121
Project Duration	11/30/2021 – 02/28/2025
Total Project Value	$ 250,000
Collaborators	Trimeric Corporation; Current Lighting Solutions, LLC; Critical Materials Institute – Ames National Laboratory
Technology Area	Rare Earth Recovery

The objective of this project was to develop a technical research plan for defining and assessing the techno-economic viability of a tunable electrochemical pathway (TEP) for producing individually separated high-purity rare earth metals and critical minerals (CM) as industrially relevant CM compounds from lignite coals and combustion byproducts originating from the Williston Basin. This project focused on technology development that advances rare earth separation into individually separated high-purity (ISHP) materials and reduction to metals. Advanced ISHP and reduction to metals processes have the potential for reduced capital costs and operating expenses compared to conventional separation and metal reduction technologies such as solvent extraction and metallothermic reduction processes.

Research, development, and demonstration (RD&D) efforts to create new domestic sources of rare earth elements (REE) and other critical minerals (CM) have been accelerated with the goal of making our domestic supply chains more resilient. Technology development and optimization of process circuits from recovery of mixed rare earth oxides/mixed rare earth salts (MREO/MRES) and CM from diverse sources, through separation into individual CM or binary high-purity REO/RES, to conversion into rare earth metals (REM) is critical to establishing a resilient domestic supply chain that is not threatened by geopolitical competition. Distributed or modular processing facilities located in close proximity to multiple feedstocks that recover and concentrate MREO and CM, could (1) enable the development of a world-class American manufacturing base and workforce in coal and power plant communities, many of which are economically distressed (the economies of coal-producing regions will be revitalized by creating local jobs that recover and refine REE and CM from coal wastes for distributed manufacturing facilities); (2) advance environmental justice in low-income communities that have been disproportionately harmed by the adverse environmental impacts associated with coal mining through remediation of coal waste materials; and (3) insulate manufacturers from disruptions in supply by consolidating the extraction and production of individual critical materials by developing tightly integrated modular systems to ensure a supply consistent both in quality and price to meet their demands.



Schematic of the tunable electrochemical pathway proposed for this project.

Production of Germanium and Gallium Concentrates for Industrial Processes

Performer	**Microbeam Technologies, Inc.**
Award Number	FE0032124
Project Duration	01/01/2022 – 12/30/2023
Total Project Value	$ 251,471
Collaborators	Barr Engineering; University of North Dakota; Dennis James Consulting, LLC; Industrial Commission of North Dakota; Lignite Energy Council; Lattice Materials, LLC; North American Coal Corporation; University of South Dakota; 5N Plus Semiconductors, LLC
Technology Area	Rare Earth Recovery

The objective of this project is to develop a conceptual design of a process to extract, separate, recover, and purify germanium (Ge) and gallium (Ga) from lignite coal-derived mixed rare earth element (MREE) concentrates. The process will be integrated into the University of North Dakota (UND) rare earth extraction process and will be designed to co-produce Ge and Ga concentrates. The potential multiphase effort involves an integrated development that spans the entire supply chain that includes feedstock sourcing, feedstock optimization, extraction, concentration, separation, refining, and product use in industrial applications. The scope of work for this project involves the development of an environmentally benign concept to produce Ge and Ga that is fully integrated with downstream applications and with the properties of the MREE species. The effort will involve the characterization of midstream feedstocks from UND's bench and pilot facilities; identification of optimal methods to recover and refine Ge and Ga for industrial applications; development of process flow diagrams of the Ge/Ga final production; and performance of a market analysis to determine the resource needed to produce quantities of refined product.

Research, development, and demonstration (RD&D) efforts to create new domestic sources of rare earth elements (REE) and other critical minerals (CM) have been accelerated with the goal of making domestic supply chains more resilient. Technology development and optimization of process circuits from recovery of mixed rare earth oxides/ mixed rare earth salts (MREO/MRES) and CM from diverse sources, through separation into individual CM or binary high-purity REO/RES, to conversion into rare earth metals (REM) is critical to establishing a resilient domestic supply chain that is not threatened by geopolitical competition.

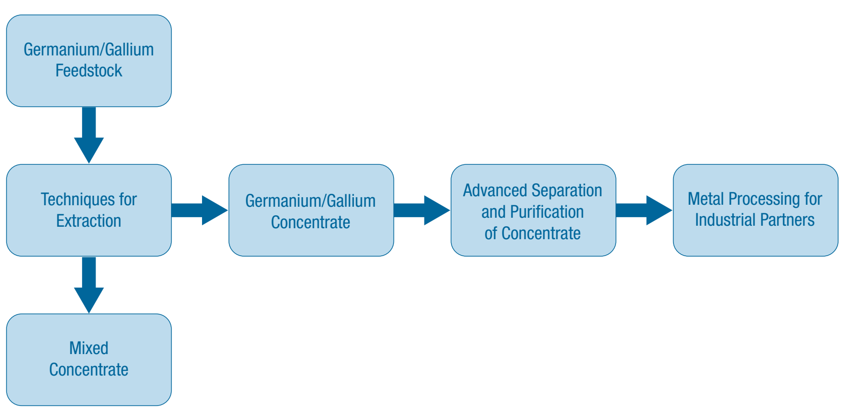


Diagram demonstrating germanium and gallium production for industrial applications.

Technology Development and Integration for Volume Production of High Purity Rare Earth Metals from Phosphate Processing

Performer	**Florida Polytechnic University**
Award Number	FE0032123
Project Duration	01/01/2022 – 09/30/2023
Total Project Value	$ 250,008
Collaborators	Pacific Northwest National Laboratory; Florida International University
Technology Area	Rare Earth Recovery

The project will develop an integrated technical research plan based on advanced processes for recovery, separation, and purification of mixed rare earth oxides (MREO) to enable mass production of rare earth metals (REM) from phosphoric acid sludge feedstock.

Phosphoric acid sludge presents a highly beneficial resource as a feedstock material for economic recovery of REEs from phosphate processing for three primary reasons: (1) rich REE content at over 2000 ppm, greater than that of most other alternative REE resources; (2) highly abundant supply; and (3) processing of this stream does not interfere with the phosphate industry's primary line of business. The research strategy involves pre-treatment of the sludge to recover both the valuable liquid phosphate fraction and REE-containing solids, leaching of REE from the solids, a novel solvent extraction technology to separate REEs from the leaching solution, and precipitation and calcination to obtain high-purity MREO, followed by advanced separation to produce REM in either individual or group form.

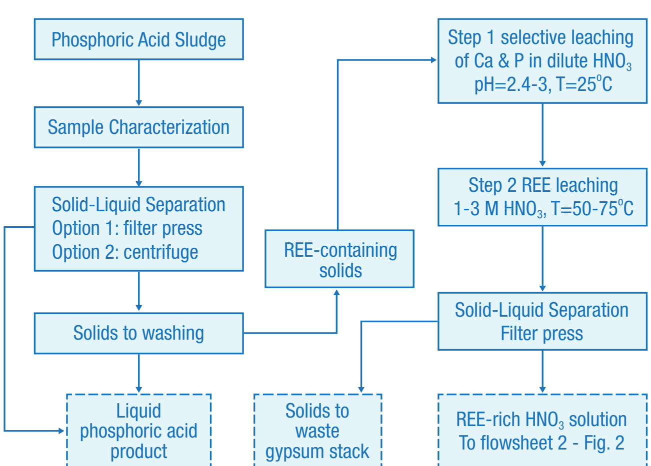


Figure 1. Conceptual Processing Flowsheet for Production of REM from Phosaphate Processing.

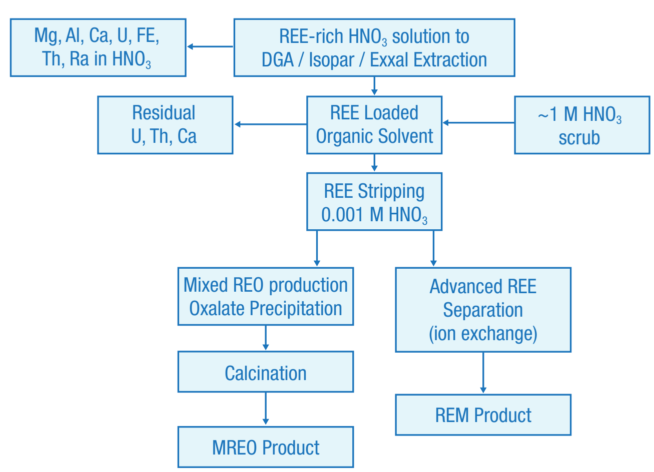


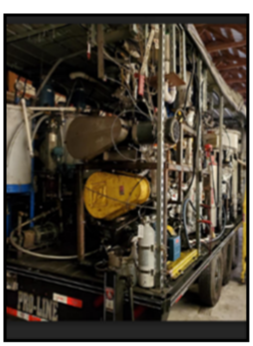
Figure 2. Flowsheet for Solvent Extraction and Advanced REE Separation.

Extraction, Separation, and Production of High Purity Rare Earth Elements and Critical Minerals from Coal-Based and Related Resources

Performer	**University of Utah**
Award Number	FE0032122
Project Duration	01/16/2022 – 04/16/2023
Total Project Value	$ 250,000
Collaborator	Virginia Polytechnic Institute and State University
Technology Area	Rare Earth Recovery

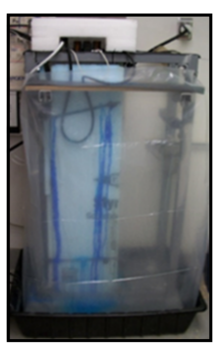
This project developed concepts for rare earth metal (REM) and critical mineral (CM) production from coal and related resources and incorporated them into a technical research plan and an innovative process flow sheet that specifies new technology. The specific project objectives included (1) identification of targeted rare earth element (REE) and critical minerals (CM) market(s), annual production quantities, demand, and intermediate/end-use products, (2) identification of a targeted set of critical materials used in these markets/applications, and as the basis for development of proposed advanced purification, separation, and reduction to metals processes, (3) selection of feedstock and existing facilities for mixed rare earth oxides (MREO)/mixed rare earth salts (MRES) and CM production, (4) identification and preliminary assessment of a process for making independently separated high-purity (ISHP) rare earth oxides (REO)/rare earth salts (RES) and CM, (5) identification and preliminary assessment of an REM production process, (6) identification and preliminary assessment of a process for conversion of CM from pilot-scale facilities to industrial CM compounds, and (7) development of a conceptual process flow diagram illustrating circuit integration for REM/CM production from coal related resources.

Success in this context was defined by the potential viability of the flow diagram for the production of the desired purified REE/CM products as well as by the potential improvements in flow diagram over conventional technologies. The ultimate success will be defined in the long term by the implementation of new technologies that enable domestic production of needed high-purity REE/CM products from coal resources.

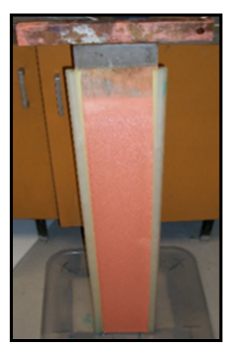


Hydrophobic-hydrophilic separation (HHS) process: Pilot scale facility

Multiple column leaching and pilot scale leaching facility (inset)



Pilot scale electrorefining facility



Electrorefined metal sheet

Pilot scale HAMR facility and high vacuum reduction setup (inset) for critical metals production

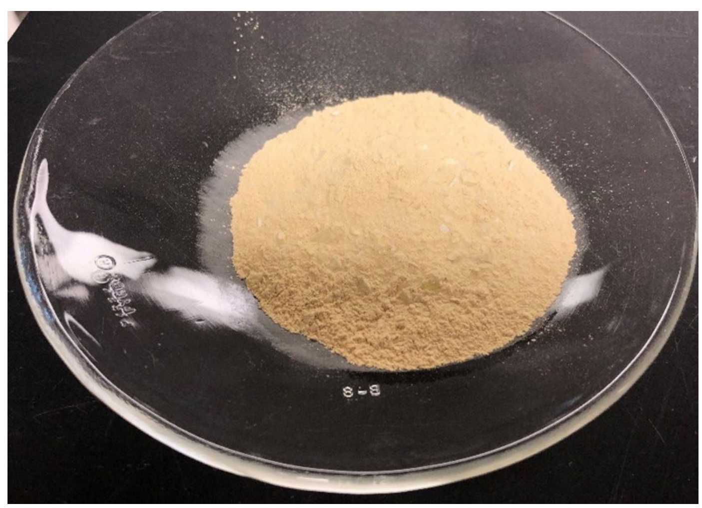
Advanced Processing of Rare Earth Elements and Critical Minerals from Acid Mine Drainage Feedstocks

Performer	West Virginia University Research Corporation
Award Number	FE0032120
Project Duration	01/14/2022 – 04/13/2023
Total Project Value	$ 249,997
Collaborators	Virginia Polytechnic Institute and State University; L3Eng; Hela Novel Metals, LLC; Northrop Grumman Corporation; Rivian Automotive, LLC; Rockwell Automation, Inc.
Technology Area	Rare Earth Recovery

This project designed, developed, and deployed innovative process technologies to produce salable rare earth metals and critical minerals from acid mine drainage (AMD) feedstocks to reduce our nation's vulnerability to interruption by international competitors. In prior efforts, the project team has successfully developed and demonstrated technology to produce mixed rare earth oxides (REO) from raw AMD in an economically attractive and environmentally benign matter. The current effort extended the process technology development further downstream to include (1) the separation of at least five individual high-purity REO and (2) the production of at least five high-purity rare earth metals and alloys. In addition, the project will explore technology to synergistically produce at least five target critical minerals (CM) during the processing steps. The development activities of this project focused on two novel technologies, namely task-specific ionic liquid separation for rare earth elements (REE) and CM separation and carboxylate reduction for the production of individually separated high-purity metals.

The team constructed a full-scale integrated 500 gpm AMD treatment plant coupled with an REE/CM facility that will produce 21 tons REE/CM per year. This plant provided feedstock for the team's proprietary downstream processes to meet the project goal: production of individually separated, high-purity REE/CM oxides and their further processing to elemental metals.

Research, development, and demonstration efforts to create new domestic sources of REE and other CM have been accelerated with the goal of making domestic supply chains more resilient. Technology development and optimization of process circuits from recovery of mixed rare earth oxides/mixed rare earth salts and CM from diverse sources, through separation into individual CM or binary high-purity REO/RES, to conversion into rare earth metals (REM) is critical to establishing a resilient domestic supply chain that is not threatened by geopolitical competition.



Sample of rare earth element material produced by members of the project team.

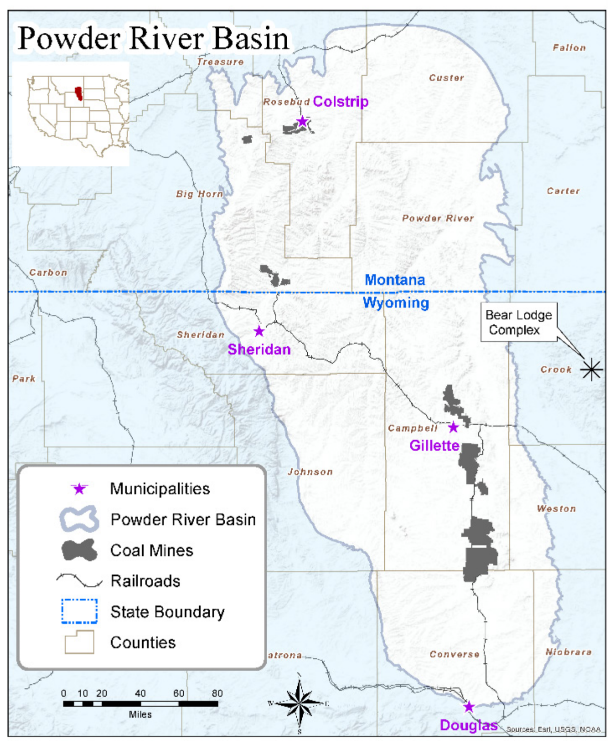
CARBON ORE, RARE EARTH, AND CRITICAL MINERALS (CORE-CM) INITIATIVE

Powder River Basin Core-Cm: Advancing Strategies for Carbon Ore, Rare Earth Element and Critical Mineral Resource Development in the Nation's Largest Coal Producing Basin

Performer	**University of Wyoming**
Award Number	FE0032048
Project Duration	09/01/2021 – 08/31/2024
Total Project Value	$ 2,084,438
Collaborators	Montana Bureau of Mines and Geology - Montana Technological University; Energy Capital Economic Development; Los Alamos National Laboratory; Battelle; Gillette College
Technology Area	Rare Earth Recovery

The objectives of this effort are to provide an economic benefit to the Powder River Basin (PRB) of Wyoming and Montana by stimulating new resource development around the nation's largest coal mines; establish strategic plans to maximize the development potential of carbon ore, rare earth element, and critical mineral (CORE-CM) resources while leveraging the highly trained workforce, existing coal technologies, energy infrastructure, and wide public acceptance of energy technology in the basin; offer a low-cost pathway to the national security benefits associated with domestic CORE-CM industries; and bring together a committed network of stakeholders from all parts of the CORE-CM value chain. The team completed initial assessments, gap analyses, and strategic plans for resource evaluation, including an initial geologic model of CORE-CM resources; CORE-CM potential of regional waste streams; infrastructure, industry, and business; technology development and field testing; technology innovation centers; and stakeholder outreach and education, including workforce development programs and forums to facilitate technology transfer.

The results obtained from this project will benefit those who live and work in the PRB, including residents in need of retraining and those just entering the workforce. Furthermore, the project results will assist in the developing a sustainable domestic industry around the existing carbon ore infrastructure in the PRB that could advance CORE-CM resource development and promote commercialization of value-added products.



Map of the Powder River Basin of Wyoming and Montana.

Bringing Alaska’s Core-CM Potential into Perspective

Performer	**University of Alaska - Fairbanks**
Award Number	FE0032050
Project Duration	09/01/2021 – 02/29/2024
Total Project Value	$ 2,533,449
Collaborators	University of Alaska - Anchorage; Alaska Division of Geophysical and Geological Surveys; JWP Consulting, LLC; ESP Research, Inc.; Technology Holdings, LLC; Ahtna, Inc.; Red Leaf Resources; University of Utah
Technology Area	Rare Earth Recovery

CORE-CM projects develop and implement strategies that enable each specific U.S. basin to realize its full economic potential for producing rare earth elements (REE), critical minerals (CM), and high-value, nonfuel, carbon-based products from basin-contained resources.

The primary objective of this project was to reduce our nation’s reliance on imported REE and CM by establishing Alaska’s resources as competitive sources of supply. The University of Alaska has documented encouraging REE/CM concentrations in preliminary studies of coal at two sites, but otherwise Alaska has not seen a systematic analysis of its resource potential. This project systematically performed a set of broad basinal assessments of Alaska’s carbon ores, rare earth elements, and critical minerals (CORE-CM) found in several of Alaska’s basins. Included in the analysis are two obvious basins: (1) that hosting Alaska’s only operating coal mine, and (2) the basin hosting North America’s largest large-flake graphite deposit.

The team also investigated opportunities to create high-value, non-fuel products from carbon ores in basins associated with REE-CM resources to increase their economic potential. Alaska contains many and varied CORE-CM basins, each with its own set of challenges. Eighty percent of Alaska is without roads, and an even greater area does not have access to the only power grid in the state, which primarily connects Fairbanks to Anchorage. The team considered factors in addition to mineral content within a basin and devised a priority matrix for ranking CORE-CM basins. Final rankings considered the quality of the CORE-CM content, access to infrastructure or ability to build it, readiness of technology to exploit the resource in that location, environmental factors, and market potential.

The results from this project have the potential to significantly contribute to our understanding of the nation’s domestic CORE-CM resources by examining for the first-time potential sources in Alaska. The project team will assess and characterize this potential with input from a full range of stakeholders. NETL is investing in establishment of a field laboratory in one of the most environmentally protected areas of the United States.

Red rock reveals a variety of minerals present in the mountains near Mt. Foraker in Denali National Park and Preserve.

Core-CM in the Greater Green River and Wind River Basins: Transforming and Advancing a National Coal Asset

Performer	University of Wyoming
Award Number	FE0032047
Project Duration	09/01/2021 – 02/29/2024
Total Project Value	$ 2,497,772
Collaborators	Los Alamos National Laboratory; Colorado Northwestern Community College; Western Wyoming Community College; Colorado School of Mines
Technology Area	Rare Earth Recovery

The overall objective of this effort is to develop and catalyze regional economic growth, job creation, and technology innovation in the greater Green River Basin (GGRB) and Wind River Basin (WRB) of Wyoming and Colorado by increasing the supply of carbon ore, rare earth elements, and critical minerals (CORE-CM) to manufacturers of non-fuel carbon-based products and products reliant upon CM. The project comprised a coalition team to describe the relationships, technology, infrastructure, and scientific understanding of these resources needed to achieve this objective.

This project will develop strategic and novel development plans for the abundant carbon ore (CORE), rare earth elements (REE), and critical minerals (CM) feedstocks located in the GGRB and WRB, including waste streams from coal, coal byproducts, trona, helium, uranium, phosphate, and oil and gas industries. The project team completed initial assessments, gap analyses, and strategic planning under several categories including (1) assessment of feedstocks, (2) waste stream reuse assessments, (3) infrastructure, industry, and businesses, (4) technology pairing and development, (5) technology innovation center planning, and (6) stakeholder outreach and education, including workforce development programs and forums to facilitate technology transfer.

The project could result in a viable pathway for a regional development opportunity, utilizing the abundant CORE-CM feedstocks located in the GGRB and WRB. Additionally, the plans developed under this project could provide CORE-CM education opportunities and information to the public.

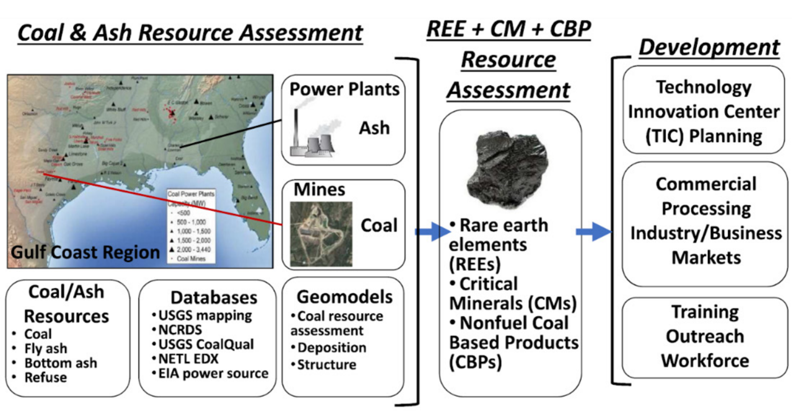
A coal sample pulled from a location within the Greater Green River and Wind River Basins of WY & CO. This sample exhibits the uniqueness of coal-based materials for CORE-CM purposes. It has high-rank coal for utility in carbon ore products as well as clay materials hosting various rare earth elements and critical minerals.

Assessment of Rare Earth Elements and Critical Minerals in Coal and Coal Ash in the U.S. Gulf Coast

Performer	**University of Texas at Austin**
Award Number	FE0032053
Project Duration	09/15/2021 – 09/30/2024
Total Project Value	$ 2,504,190
Collaborators	Geological Survey of Alabama; United States Geological Survey (USGS); University of Kentucky; University of North Dakota Institute of Energy Studies; University of Wyoming
Technology Area	Rare Earth Recovery

The objectives of the study are to quantify rare earth elements (REE) and critical minerals (CM) resources in feedstocks within the U.S. Gulf Coast Basin including coal from mines, coal ash from power plants, and refuse. REE and CM will also be quantified in water co-produced with oil in reservoirs adjacent to coal resources. Additional objectives include linking these mineral resources to manufacturing of high-value products, including nonfuel carbon-based products (CBPs), planning the development of a technology innovation center, and stakeholder outreach and education to achieve the overall goal of enhancing economic growth and job creation to support economic development in the Gulf Coast. The methods involve development of coal and ash resource assessments by leveraging previous coal assessments and using power plant ash data. The geological assessment involves mapping the resources and considering depositional environments and structural data, resulting in a detailed geomodel of the Gulf Coast coals.

Analysis of REE and CM in approximately 200 samples of coal and ash are designed to substantially expand the existing database and deepen our understanding of the potential for these resources. The Gulf Coast Basin has many surface lignite mines that have been highly under-sampled for REE and CM; however, potential REE and CM resources may be as high as shown in studies of North Dakota lignite. In addition, much of the coal combusted in power plants in the Gulf Coast over the past decade is sourced from the Powder River Basin in Wyoming, which has been shown to be promising in terms of REE and CM recovery. The intensive industrialization in the Gulf Coast region represents a large market for REE and CM products. The comprehensive assessment of REE and CM is designed to evaluate the volumes of these feedstocks and link upstream and midstream supply chains with downstream processing and manufacturing to enhance U.S. national and economic security.



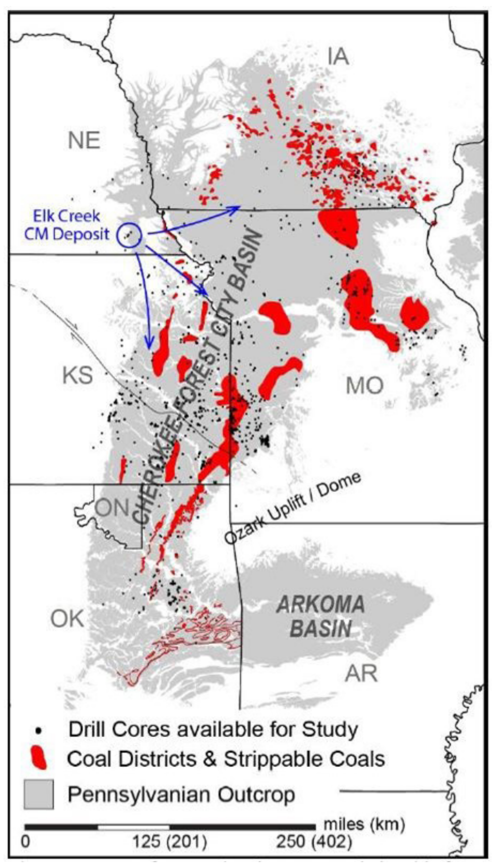
Assessment approach.

Critical Minerals in Coaly Strata of the Cherokee-Forest City Basin

Performer	**University of Kansas Center for Research**
Award Number	FE0032056
Project Duration	09/15/2021 – 09/14/2024
Total Project Value	$ 2,606,250
Collaborators	Iowa Geological Survey; Kansas Geological Survey; Missouri Geological Survey; Nebraska Geological Survey; Oklahoma Geological Survey; Osage Nation
Technology Area	Rare Earth Recovery

The overall objective is to integrate new and legacy critical mineral (CM) geochemical data with new basin-wide stratigraphic correlations of coal resources and genetically related strata within the greater Cherokee-Forest City Basin (CFCB) which encompasses parts of Kansas, Iowa, Missouri, Nebraska, Oklahoma, and Osage Nation. Analyses will include new and/or existing drill cores located throughout the basin and assays from coal mine waste sites in historic mine districts to assess the rare earth elements (REE) and critical mineral potential within the region. The performer will also test a novel downhole elemental analysis tool at a number of new and/or existing well localities that are proximal and reliably correlated to drill cores.

This study will encompass: (1) a basinal assessment of carbon ore, rare earth, and critical mineral (CORE-CM) resources, including aggregation of historical data, new depositional and structural modeling, and CORE-CM resource assessment; (2) development of a basinal strategy for reuse of waste streams and assist in the development of necessary infrastructure needed to mine and process both natural and waste REE/critical mineral materials; (3) development of a technology assessment and field-testing plan to identify technology gaps associated with the mining process and ways in which the mining technique may be improved; (4) planning for a technology innovation center that fosters public-private partnerships (providing a nucleus of expertise and facilities) that are focused on rapid commercialization of CORE-CM resources within the basin and identification of emerging technologies that can incorporate coal and coal byproducts as a feedstock; and (5) development of a stakeholder outreach and education plan that will include educational forums, workshops, digital media, and publications.



Map of Pennsylvanian outcrop belt with former coal mine districts and near-surface strippable coals.

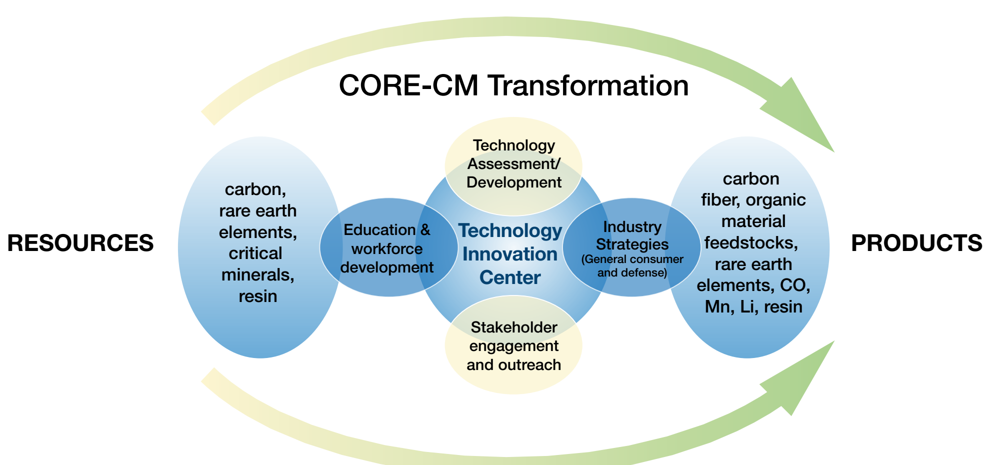
Transforming Uinta Basin Earth Materials for Advanced Products (Tube-Map)

Performer	**University of Utah**
Award Number	FE0032046
Project Duration	09/15/2021 – 08/14/2024
Total Project Value	$ 2,567,777
Collaborators	Colorado School of Mines; JWP Consulting, LLC; Los Alamos National Laboratory; Utah Advanced Materials and Manufacturing Initiative; Utah Geological Survey; Utah State University Eastern; Wolverine Fuels, LLC
Technology Area	Rare Earth Recovery

CORE-CM projects will develop and implement strategies that enable each specific U.S. basin to realize its full economic potential for producing REE, CM and high-value, nonfuel, carbon-based products from basin-contained resources. CORE-CM projects will focus on the following six objectives: (1) basinal assessment of CORE-CM resources, (2) basinal strategies for reuse of waste streams, (3) basinal strategies for infrastructure, industries, and businesses, (4) technology assessment, development, and field testing, (5) technology innovation centers, and (6) stakeholder outreach and education.

The objectives of this project were to quantify, assess, and develop a plan to enable the transformation of Uinta Basin earth resources such as coal, oil shale, resin, rare earth elements, and critical materials into high-value metal, mineral, and carbon-based products that can be used in advanced products such as carbon fiber composites in aircraft and high-powered magnets and batteries in electric vehicles. The transformation begins with understanding the geology, which enables discovery of value-added resources, followed by innovative mining to optimize resource recovery, metallurgical processing to separate minerals and purify metals, chemical engineering to enable production of value-added carbon-based products, training and education to prepare the workforce, stakeholder engagement and outreach to facilitate sustainable development, and industry support to drive implementation and manufacturing.

This project included large-scale extraction of multiple resources that can, through integrated and innovative processing, be used to produce multiple value-added products and create new industries as well as a more diversified Uinta Basin economy.



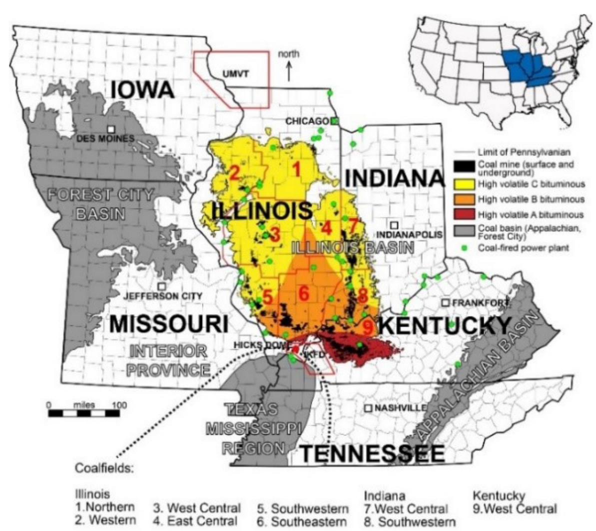
Illinois Basin Carbon Ore, Rare Earth, and Critical Minerals Initiative

Performer	**University of Illinois Urbana-Champaign – Illinois State Geological Survey**
Award Number	FE0032049
Project Duration	09/21/2021 – 03/20/2024
Total Project Value	$ 2,476,926
Collaborators	Southern Illinois University; University of Kentucky; Tennessee Geological Survey; Kentucky Geological Survey; SynTerra Corp.; Oak Ridge National Laboratory; Iowa Geological Survey; Indiana Geological and Water Survey
Technology Area	Rare Earth Recovery

Carbon ore, rare earths, and critical minerals (CORE-CM) projects focus on six objectives: (1) basinal assessment of CORE-CM resources, (2) basinal strategies for reuse of waste streams, (3) basinal strategies for infrastructure, industries, and businesses, (4) technology assessment, development, and field testing, (5) technology innovation centers, and (6) stakeholder outreach and education. This Illinois Basin (IB) CORE-CM project will evaluate the domestic occurrence of strategic elements in coal, coal-based resources, and waste streams from coal use in the region of the IB. The Illinois State Geological Survey-led project will conduct a basin-wide assessment of CORE-CM in coal, coal-based, and waste stream resources that will include CORE-CM availability and abundances. Additionally, the project will assess the mining practices, separation technologies, and local infrastructure necessary to produce and provide CORE-CM resources for U.S. industry and stimulate regional economic growth.

The project team performing this work includes state geological surveys, regional universities, national laboratories, and industries active in the region of Illinois, Indiana, Iowa, Kentucky, and Tennessee. The Illinois Basin assessment will catalog and model existing geochemical and geological data to identify areas of CORE-CM resources in the area having potential economic viability. Regional infrastructure, industries, and businesses, either existing or required to integrate and utilize CORE-CM resources in the IB, will be evaluated. A strategic stakeholder and outreach program will be designed to engage relevant industries and commercial interests. Technologies most relevant to the Illinois Basin distribution and occurrence of CORE-CM in relation to mining techniques, the processing and separation of CORE-CM, and the incorporation of CORE-CM into products will be identified, characterized, and described.

A technology innovation center will be developed to address IB CORE-CM-specific analytical challenges, extraction requirements, resource assessments, and product creation and will serve as a focus for outreach, industry participation, and the pursuit of commercial opportunities. CORE-CM projects will develop and implement strategies that enable each specific U.S. basin to realize its full economic potential for producing rare earth elements, critical minerals and high-value, nonfuel, carbon-based products from basin-contained resources.



Simplified map of the Illinois Basin showing nine distinct coal-producing areas. UMVT = Upper Mississippi Valley type; IKFD = Illinois-Kentucky Fluorspar District.

Consortium to Assess Northern Appalachia Resource Yield (CANARY) of CORE-CM for Advanced Materials

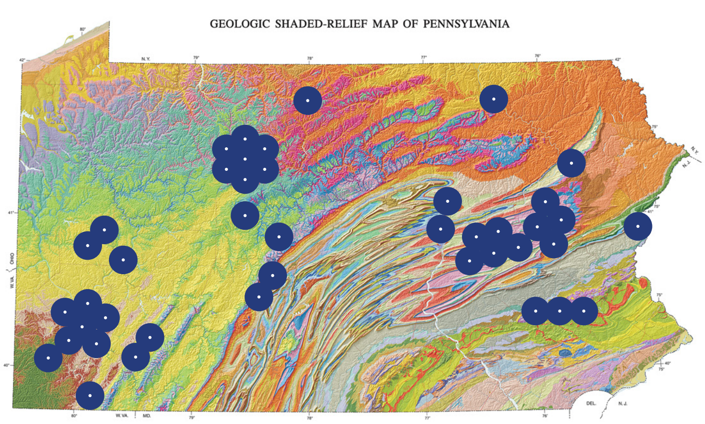
Performer	**Pennsylvania State University**
Award Number	FE0032052
Project Duration	10/01/2021 – 06/30/2024
Total Project Value	$ 2,209,624
Collaborators	Colorado School of Mines; Tetra Tech, Inc.; University of Kentucky Research Foundation; Virginia Polytechnic Institute and State University
Technology Area	Rare Earth Recovery

The Consortium to Assess Northern Appalachia Resource Yield (CANARY) of CORE-CM for Advanced Materials comprises university, private industry, and state, local, and federal government personnel to evaluate the carbon ore, rare earth element, and critical mineral (CORE-CM) production potential of the Northern Appalachian (NA) basin covering, Maryland, Ohio, Pennsylvania, and West Virginia. CORE-CM projects will develop and implement strategies that enable each specific U.S. basin to realize its full economic potential for producing REE, CM and high-value, nonfuel, carbon-based products from basin-contained resources. CORE-CM projects will focus on the following six objectives: (1) basinal assessment of CORE-CM resources, (2) basinal strategies for reuse of waste streams, (3) basinal strategies for infrastructure, industries, and businesses, (4) technology assessment, development, and field testing, (5) technology innovation centers, and (6) stakeholder outreach and education.

The proposed project will build on prior work by and current expertise of Penn State and other leading research universities and industrial partners, including some who currently own, develop, and operate carbon ore and critical mineral plants in the United States. CANARY will also collaborate with U.S. and state geological surveys and will review the USGS National Geochemical Database, ongoing efforts of the Earth Mapping Resources Initiative, historic mining and processing sites, and data currently held by the project team members.

To identify information gaps, the consortium will use GIS and machine learning applications to map the resource, infrastructure, and market data in consultation with NETL Research and Innovation Center geospatial modeling activities. Research needs and technology gaps will be assessed, and resources targeted for sampling and characterization. This effort will provide a complete Northern Appalachian CORE-CM value chain basinal assessment to enable quick development of commercial projects.

CANARY will catalyze regional growth and job creation related to CORE-CM as we envision the capability of domestic production of these critical components needed for future development of an advanced, technology-driven society.



Locations of carbon material and critical mineral companies in PA (Rozelle, 2020b).

Williston Basin CORE-CM Initiative

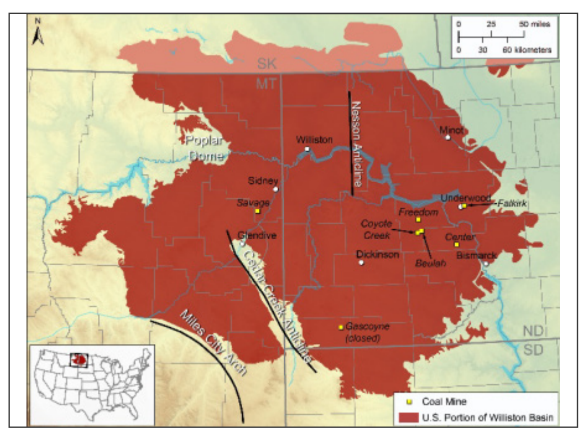
Performer	**University of North Dakota Energy & Environmental Research Center (UNDEERC)**
Award Number	FE0032060
Project Duration	10/01/2021 – 03/31/2024
Total Project Value	$ 3,142,750
Collaborators	Ames National Laboratory, Montana Tech of the University of Montana, North Dakota State University, Pacific Northwest National Laboratory
Technology Area	Rare Earth Recovery

CORE-CM projects focus on the following six objectives: (1) basinal assessment of CORE-CM resources, (2) basinal strategies for reuse of waste streams, (3) basinal strategies for infrastructure, industries, and businesses, (4) technology assessment, development, and field testing, (5) technology innovation centers, and (6) stakeholder outreach and education.

The project team, a coalition of nearly 30 partners encompassing all value chain segments, focused on expanding the use of coal and coal-based resources to produce rare earth elements (REE), critical minerals (CM), and nonfuel carbon-based products in the Williston Basin. This basin, centered in western North Dakota with portions reaching into South Dakota, Montana, and Canada, contains over 800 years of lignite coal at existing rates of use. The primary development of Williston Basin lignite coal has been in North Dakota, providing coal resources to a series of power facilities totaling greater than 4000 MW of generation capacity. The project work constituted Phase 1 of a long-term program with objectives to identify the existing knowledge base and gaps and to develop a series of assessments/plans. Research was conducted to identify and compile the existing extensive Williston Basin knowledge base related to REE, CM, and nonfuel carbon-based products.

Specific efforts focused on assessment of coal characteristics, identification of waste streams available, development of regional business planning opportunities, assessment of existing technologies, development of plans to create technology innovation centers, and stakeholder outreach. This assessment resulted in databases, models, and a series of assessments/plans that are intended to guide the next phase of activities, with the overall goal of expanding and transforming the use of coal and coal-based resources within the Williston Basin.

The results of this project work could help to catalyze regional economic growth and job creation.



Map of the Williston Basin.

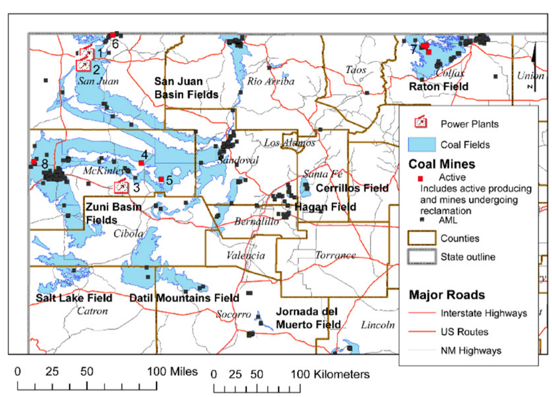
Carbon Ore, Rare Earth, and Critical Minerals (CORE-CM) Assessment of San Juan River-Raton Coal Basin, New Mexico

Performer	**New Mexico Institute of Mining and Technology**
Award Number	FE0032051
Project Duration	10/01/2021 – 09/30/2024
Total Project Value	$ 2,570,930
Collaborators	Sandia National Laboratories; Los Alamos National Laboratory; San Juan College; SonoAsh, LLC
Technology Area	Rare Earth Recovery

The specific objective of this project is to determine the REE and CM resource potential in coal and related stratigraphic units in the San Juan and Raton Basins, New Mexico. The project will (1) identify and quantify the distribution of REE and CM in coal beds and related stratigraphic units in the San Juan and Raton basins, (2) identify and characterize the sources of REE and CM, and (3) evaluate the basinal industry infrastructure and determine the economic viability of industrial upgrading. New Mexico Tech will (1) conduct a basinal assessment for CM and REE potential, using state-of-the-art technologies to estimate basin-wide CM and REE resources in coal and related stratigraphic units; (2) identify, sample, and characterize coal waste stream products; (3) conduct bench tests to develop a basinal reuse of waste strategy; (4) illustrate the current status of the feedstock supply of REE and CM to understand the basinal REE industry's capital expenditures and obstacles to expanding REE-related business development; (5) develop a life-cycle analysis to establish pathways, process engineering, and design requirements to upgrade REE processing industry, (6) evaluate technology gaps, (7) establish a Center of Excellence (COE) and training center for coal ash beneficiation in San Juan County; and (8) create REE research-based activities that can be shared during the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) summer geology teacher workshop and assemble REE research-related articles for a REE-centered issue of *Lite Geology*.

This project will delineate favorable geologic terranes and priority areas containing potential REE and CM deposits for the DOE mandate, which is also a priority of the New Mexico Bureau of Geology and Mineral Resources and the State of New Mexico. This project also is important to the New Mexico because REE and CM resources must be identified before land use decisions are made by government officials.

Future mining of REE and CM will directly benefit the economy of New Mexico. Furthermore, it is crucial to re-establish a domestic source of REE and CM in the United States to help secure the nation's clean energy future, reducing the vulnerability to material shortages related to national defense, and to maintain our global technical and economic competitiveness. Another aspect of this project is the training of the future workforce because students at New Mexico Tech and San Juan College will be hired to work on this project. Sampling locations include active and inactive mines, and post-combustion coal ash landfills.



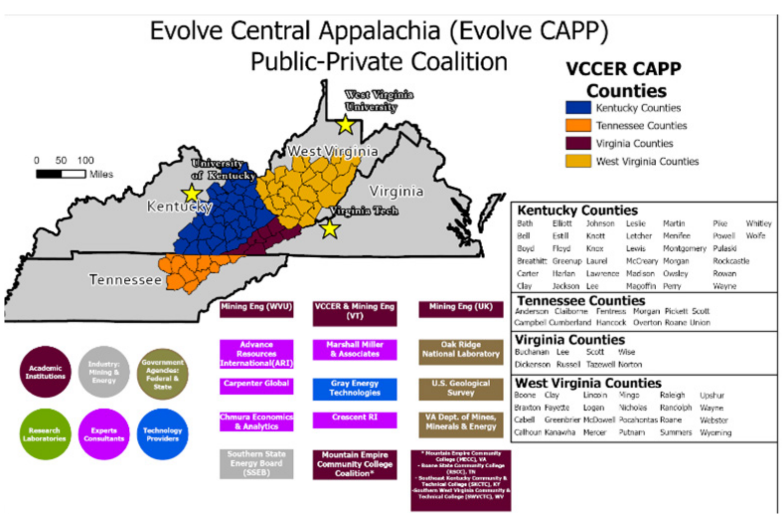
Location of coal fields, active and inactive mines, and coal burning power plants in the project area.

Evolve Central Appalachia (Evolve CAPP)

Performer	**Virginia Polytechnic Institute and State University**
Award Number	FE0032055
Project Duration	10/01/2021 – 03/31/2024
Total Project Value	$ 2,708,867
Collaborators	West Virginia University; University of Kentucky; Marshall Miller and Associates, Inc.; Advanced Resources International; Virginia Department of Energy; Mountain Empire Community College; Crescent Resource Innovation; Gray Energy Technologies, LLC; Chmura Economics & Analytics, LLC; Southern States Energy Board; U. S. Geological Survey; Oak Ridge National Laboratory
Technology Area	Rare Earth Recovery

Project-specific objectives are to determine the quantity and distribution of CORE-CM resources in the region, formulate strategies to utilize coal waste streams to produce useful fuels and materials, formulate strategies to encourage business development, guide research and development of new technologies, formulate plans to establish technology innovation centers, and formulate and implement stakeholder outreach and education initiatives. In addition, the research team will evaluate regional infrastructure and identify industries and businesses that may benefit from current and future CORE-CM production and utilization. Strategies will be presented to spur economic growth, close supply chain gaps, promote investment in the region, and address workforce education and training opportunities.

The team will collaborate with business and industrial partners to accelerate commercial deployment of promising technologies that can recover and utilize CORE-CM resources in an environmentally and socially responsible manner. National interest and U.S. independence in critical raw materials and national security will be addressed in the overall technology assessment process. This project could help to reduce U.S. dependence on foreign sources of REE and CM by utilizing the region's vast natural resources and skilled workforce to extract additional CORE-CM resources from coal and associated byproducts to develop additional revenue streams through the manufacture of intermediate and end-use carbon-based products.



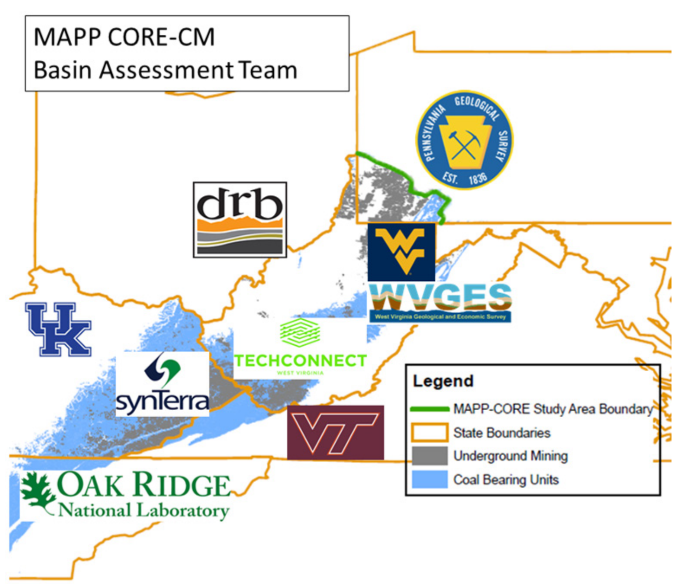
Mid-Appalachian Carbon Ore, Rare Earth and Critical Minerals Initiative

Performer	**West Virginia University Research Corporation**
Award Number	FE0032054
Project Duration	10/01/2021 – 02/29/2024
Total Project Value	$ 2,827,128
Collaborators	University of Kentucky; Virginia Polytechnic Institute and State University; West Virginia Geological and Economic Survey; Pennsylvania Department of Conservation and Natural Resources; SynTerra Corporation; Oak Ridge National Laboratory; DRB Geological Consulting; TechConnect West Virginia
Technology Area	Rare Earth Recovery

CORE-CM projects will develop and implement strategies that enable each specific U.S. basin to realize its full economic potential for producing rare earth elements (REE), critical minerals (CM), and high-value, nonfuel, carbon-based products from basin-contained resources. CORE-CM projects will focus on six objectives: (1) basinal assessment of CORE-CM resources, (2) basinal strategies for reuse of waste streams, (3) basinal strategies for infrastructure, industries, and businesses, (4) technology assessment, development, and field testing, (5) technology innovation centers, and (6) stakeholder outreach and education.

The overall objective of the West Virginia University Research Corporation (WVURC) in this project will be to focus on the expansion and transformation of the use of coal and coal-based resources—including waste streams—to produce products of high value to the 21st century energy and manufacturing ecosystem. The project will accomplish these goals via a basin assessment of Central Appalachian resources, including waste streams, that could be reused as feedstocks and raw materials in processes that produce carbon ore, rare earth and critical minerals (CORE-CM) products. The team will prepare R&D plans to fill information gaps in the assessments of CORE-CM resources and regional waste streams. A technology and economic gap assessment to address barriers and spur growth for the basin's CORE-CM resources will be developed, including preparing initial research plans to fill those gaps. In addition, the team will prepare plans for stakeholder outreach and education needed to support these activities. This effort will culminate with the preparation of initial plans for a technology innovation center that will be developed and operated by a basin-specific public-private partnership, leveraging facilities and resources of the MAPP-CORE team.

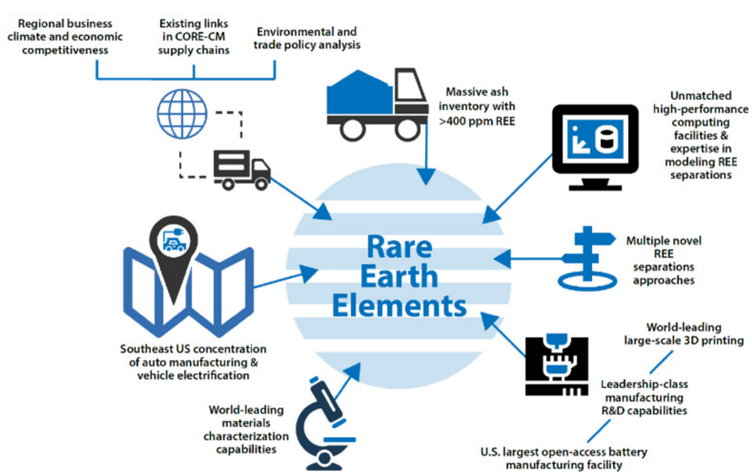
This project will perform the initial strategy development and economic and technical gap assessment for the mid-Appalachian region, defined as the states of Kentucky, Tennessee, Virginia, and West Virginia. The project team also includes resource assessments for southwestern Pennsylvania, recognizing the geologic and geographic connections between these regions.



Manufacturing Valuable Coal-Derived Products in Southern Appalachia

Performer	**Collaborative Composite Solutions Corporation**
Award Number	FE0032045
Project Duration	09/15/2021 – 07/31/2024
Total Project Value	$ 2,607,746
Collaborators	Geological Survey of Alabama; Southern Company Services, Inc.; University of Alabama; University of Alabama at Birmingham; University of Tennessee
Technology Area	Rare Earth Recovery

The Institute for Advanced Composites Manufacturing Innovation, or IACMI—The Composites Institute—is a national Manufacturing USA Institute managed by Collaborative Composite Solutions Corporation (CCS). CCS developing strategies for manufacturing valuable non-fuel products from coal in Southern Appalachia. The project focuses on using coal resources from the southern Appalachian Basin situated in east Tennessee, northwest Georgia, and northern Alabama. Key participants include the University of Tennessee, Southern Company, state geological surveys of Alabama and Tennessee, Oak Ridge National Laboratory, University of Alabama, University of Alabama at Birmingham, Roane State Community College, and several other stakeholders that are informally supporting the project. The project is assessing the southern Appalachian Basin's coal resources and identifying strategies for developing technologies to cost-effectively produce valuable non-fuel products from those resources. The program objective is to transform distressed coal communities into thriving manufacturing communities with high-wage jobs producing coal-based products. Initial product priorities include rare earth elements extracted from coal ash, as well as carbon fibers and graphite made from coal. Potential product applications include (i) automobiles, capitalizing on the region's vibrant automotive manufacturing industry and the emergence of electric vehicles manufacturing; and (ii) resilient infrastructure that can withstand natural events such as hurricanes, tornadoes, and floods that frequently occur in the southeastern United States. Critical project elements include economics and policy analysis on the interrelationships and risks or resource availability, market demand, supply chains, infrastructure, workforce, tax and regulatory policy, technology, and national security.



Southern Appalachian REE Ecosystem.

CRITICAL MINERALS FROM PRODUCED WATERS

Low-Cost Environment-Friendly Critical Materials Recovery from Produced Water

Performer	**Altex Technologies Corporation**
Award Number	SC0022939
Project Duration	06/27/2022 – 03/26/2023
Total Project Value	$ 199,994
Collaborator	Pennsylvania State University
Technology Area	Rare Earth Recovery

This project developed low-cost, low energy consumption, and environmentally-friendly technologies to recover critical minerals and materials (CMM), including rare earth elements (REE), from oil-field produced water (PW). Currently, the United States is heavily dependent on foreign markets for REE and CMM, and thus domestic sources are desired to secure supply chains. Additionally, current disposal methods of PW are plagued by high energy consumption and expenses, and present seismic, climate, health, and toxicology concerns. Accordingly, this effort aimed to address these challenges by reducing the costs of REE recovery and PW treatment.

In this project, a novel sorption technology which leverages a metal organic framework (MOF) was used to recover critical materials from PW. Material synthesis and characterization, demonstration of the sorption technology, development of a full-scale design, techno-economic assessment (TEA), and life cycle analysis (LCA) of the full-scale process was performed. Currently available sorbent materials were improved and optimized to increase the percentage of REE recovered and address selective recovery of a wider range of materials. Analysis, lab-scale fabrication, and testing was used to achieve this goal. Lab-scale test data was used to optimize the process design and demonstrate the technical and economic feasibility of the innovation. It is anticipated that commercialization of the proposed technology could significantly lower the cost of REE and reduce dependency on volatile external markets.

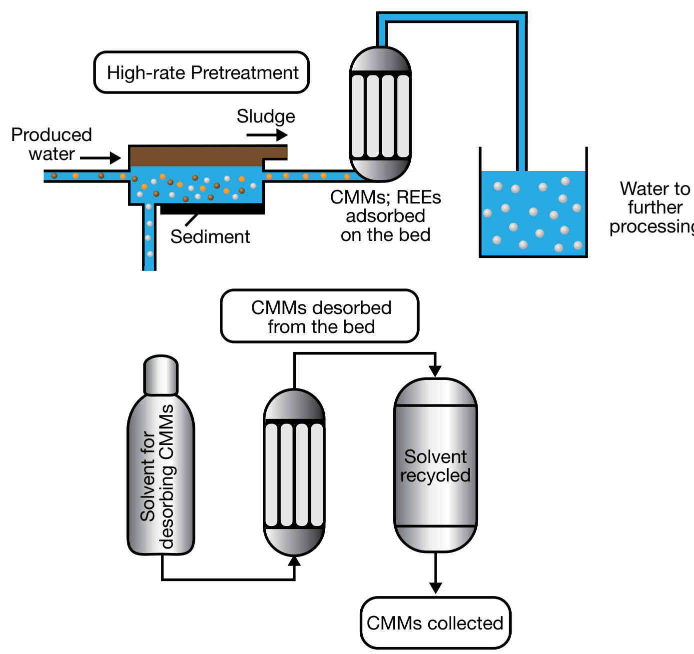
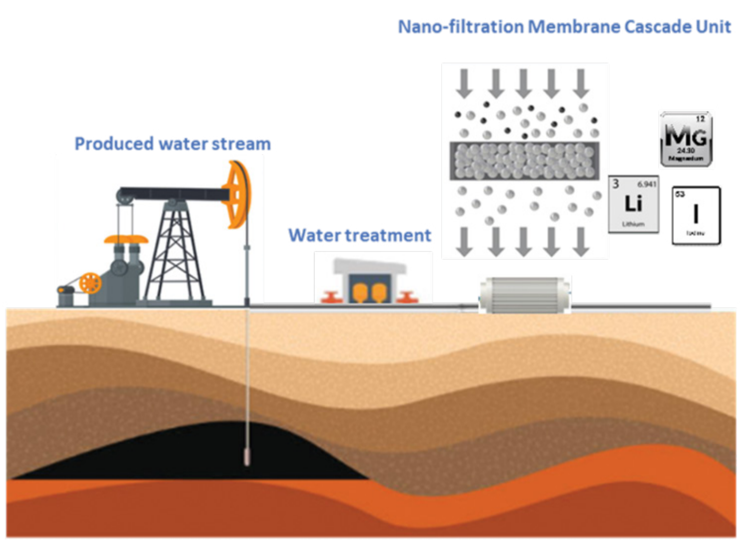


Diagram demonstrating low-cost environmentally friendly critical materials recovery from produced water.

Extraction of Value-added Minerals from Produced Water Through Novel Multistage Nanofiltration

Performer	**Greenpath Systems, LLC.**
Award Number	SC0022863
Project Duration	06/27/2022 – 06/26/2023
Total Project Value	$ 199,948
Collaborators	University of Oklahoma
Technology Area	Rare Earth Recovery

Recent growth in oil and gas production through fracking has increased the amount of generated wastewater, known as produced water, that requires treatment in order to meet environmental regulations. Wastewater treatment processes may employ several types of membranes, including microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF). The main difference in these processes is the solute size that can be separated from the wastewater stream. For example, while typical UF membranes have pore sizes of 10–100 nm and are used to remove proteins, organic acids, oil emulsions, microbes, and viruses from wastewater, NF membranes with 1–5 nm pore sizes can separate monovalent and multivalent ions based on the charge and size. Typical produced waters contain magnesium (Mg) and bromine (Br) on the order 1000 ppm, and lithium (Li), boron (B), barium (Ba), and iodine (I) on the order of 50 ppm. Therefore, produced water presents an opportunity as an unconventional resource, which may support the expanded requirement for Li necessary for technologies such as Li-ion batteries and may also support increased domestic supply of Mg. In this project, a multistage NF process leveraging NF membranes with different pore sizes was employed to separate Li and Mg salts from one another, as well as other species present in produced water.

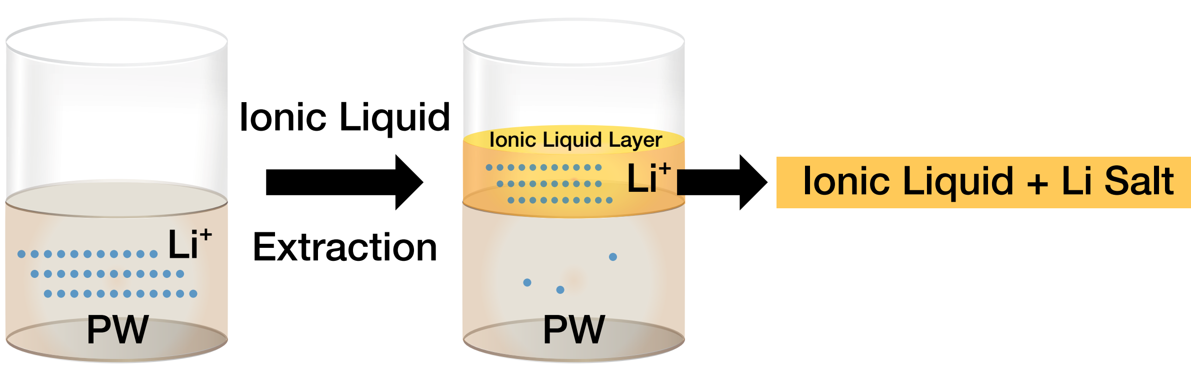


Extraction of value-added minerals from produced water.

Critical Minerals and Materials Recovery from Oil and Gas Produced Water

Performer	**Materials Modification Inc.**
Award Number	SC0022866
Project Duration	06/27/2022 – 03/26/2023
Total Project Value	$ 200,000
Collaborator	University of Wyoming
Technology Area	Rare Earth Recovery

In this project, lithium (Li) was selectively recovered from produced water using a liquid-liquid solvent extraction process, employing selectively functionalized ionic liquids as solvents. The extraction behavior was analyzed as a function of various parameters including produced water dilution, acidity, temperature, ionic liquid type, and the addition of co-solvents. The extraction efficiencies obtained in these studies were benchmarked against a traditional solvent used in metal ion extraction. In addition, the efficiency of Li extraction using the ionic liquid and the recyclability of the ionic liquid itself were studied. The United States lacks secure and resilient critical minerals supply chains necessary for a robust conversion to clean energy technologies. This project supported the programmatic goal of developing low-cost, low-energy, and environment-friendly technologies to recover critical minerals and materials, including rare earth elements, from the produced waters from oil, natural gas, and carbon storage operations.



Concept of ionic liquid extraction.

ABBREVIATIONS

AMD ... acid mine drainage
CANARY ... Consortium to Assess Northern Appalachia Resource Yield
CBP ... carbon-based products
CCS ... Composite Solutions Corporation
CM ... critical mineral(s)
CMM ... critical minerals and materials
CORE-CM ... carbon ore, rare earth element, and critical mineral
DOE ... Department of Energy
DTPA ... diethylenetriaminepentaacetic acid
Dy ... dysprosium
FECM ... Office of Fossil Energy and Carbon Management
FEED ... front end engineering design
FWP ... Field Work Proposal
FY ... fiscal year
HREE ... heavy rare earth element(s)
IACM ... Institute for Advanced Composites Manufacturing Innovation
IB ... Illinois Basin
ISHP ... individually separated high purity
LANL ... Los Alamos National Laboratory
LIBS ... laser induced breakdown spectroscopy
LLNL ... Lawrence Livermore National Laboratory
LREE ... light rare earth element(s)
MREO ... mixed rare earth oxide(s)
MRES ... mixed rare earth salt(s)
NA ... Northern Appalachian
ND ... North Dakota
NETL ... National Energy Technology Laboratory
NM ... New Mexico
PNNL ... Pacific Northwest National Laboratory
ppb ... parts per billion
ppm ... parts per million
Pr ... praseodymium
PRB ... Powder River Basin
R&D ... research and development
RD&D ... research, development, and demonstration
REE ... rare earth element(s)
REM ... rare earth metal(s)
REO ... rare earth oxide(s)
RES ... rare earth salt(s), Rare Earth Salts (company)
RIC ... Research and Innovation Center
SBIR ... small business innovative research
SSLiB ... solid state Li-ion battery
TCF ... Technology Commercialization Fund
TEA ... techno-economic analysis
TEP ... tunable electrochemical pathway
Tpd ... tonne(s) per day
TRL ... technology readiness level
UK ... University of Kentucky
UK CAER ... University of Kentucky Center for Applied Energy
UMVT ... Upper Mississippi Valley type
UND ... University of North Dakota
UNDEERC ... University of North Dakota Energy and Environment Research
WRB ... Wind River Basin
Wt ... weight
WVURC ... West Virginia University Research Corporation

NOTES

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https://edx.netl.doe.gov/ree-cm/

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