U.S. Department of ENERGY

Minerals Sustainability Multi-Year Program Plan

January 2025

List of Acronyms

AAMMTO	Advanced Materials and Manufacturing Technology Office
CMC	Critical Materials Collaborative
CMI	Critical Materials Innovation Hub
CMM	Critical Minerals and Materials
DHS	U.S. Department of Homeland Security
DMS	Division of Minerals Sustainability
DOC	U.S. Department of Commerce
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOS	U.S. Department of State
DOT	U.S. Department of Transportation
EERE	Office of Energy Efficiency and Renewable Energy
EPA	U.S. Environmental Protection Agency
ES&H	Environment Safety and Health
EV	Electric Vehicle
FDM	Fused Deposition Modeling
FEED	Front End Engineering and Design
FECM	Office of Fossil Energy and Carbon Management
FT-IR	Fourier-Transform Infrared Spectroscopy
GDP	Gross Domestic Product
HR-ICP-OES/MS	High Resolution-Inductive Coupled Plasma-Optical Emission Spectrometry Mass Spectrometry
IA	Office of International Affairs
ISHP	Individually Separated High-Purity
ISO	International Organization for Standardization
LA-ICP-MS	Laser Ablation Inductively Couple Plasma- Mass Spectrometry
LIBS	Laser Induced Breakdown Spectroscopy
LCA	Life Cycle Analysis
LiDAR	Light Detection and Ranging
LPO	Loan Programs Office
MESC	Office of Manufacturing and Energy Supply Chains

MREO	Mixed Rare Earth Oxides
MRES	Mixed Rare Earth Salts
NASA	National Aeronautics and Space Administration
NE	Office of Nuclear Energy
NETL	National Energy Technology Laboratory
NIST	National Institute for Standards and Technology
NNSA	National Nuclear Security Administration
NSF	National Science Foundation
NSTC	National Science and Technology Council
OSMRE	Office of Surface Mining Reclamation and Enforcement
OTT	Office of Technology Transfer
PGEs	Platinum Group Elements
PPM	Parts Per Million
R&D	Research and Development
REE	Rare Earth Element
REO	Rare Earth Oxides
RES	Rare Earth Salts
RFI	Request for Information
SC	Office of Science
SEM	Scanning Electron Microscopy
SLA	Stereolithography
TC	Technical Committees
TEA	Techno-Economic Analysis
TRL	Technical Readiness Levels
TSMC	Taiwan Semiconductor Manufacturing Company
USGS	U.S. Geological Survey
VOC	Volatile Organic Compound
XANES	X-ray Absorption Near Edge Structure

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1. Overview

Domestic production of minerals and metals that form the backbone of our society is essential to our economic prosperity, achieving our environmental goals, and strengthening national defense.[1] The United States was once a global leader in producing these minerals, but over the last few decades, America's import dependency on critical minerals and materials (CMM) has continued to worsen,[2] and there is near-universal agreement that investments to speed the development of domestic CMM supply chains are an urgent national priority.[3]

The US has no domestic production of at least 14 of the 50 critical minerals according to the latest critical minerals assessment from the U.S. Geologic Survey. Though the U.S. does produce 36 of the remaining critical minerals, almost none of them are produced in quantities that meet even half our domestic demand (Figure 1).[4] This foreign import dependency for the minerals and materials that drive our economy is steadily increasing significant economic, energy, and security risks for the Nation.[5]

The U.S. Department of Energy (DOE) has established a nationwide portfolio of CMM activities that support development of reliable, resilient, affordable, diverse, sustainable, and secure domestic CMM supply chains. These materials are necessary to the functioning of domestic communication, energy, manufacturing, and transportation economies.[6]

As part of DOE's overall strategy, the Office of Fossil Energy and Carbon Management (FECM), has focused on the development of a resilient circular CMM supply chain from abundant domestic unconventional and secondary mineral sources (Figure 2 and Table 1), with the potential to: (1) accelerate the production of domestic critical minerals, while addressing environmental waste and degradation; (2) revitalize domestic manufacturing and refining capabilities in industrial communities; and (3) create new jobs in the critical mineral, metallurgical, and environmental sectors—especially in some regions being heavily impacted by job losses, e.g. coal communities.

Figure 1. 2023 U.S. Net Import Reliance. From USGS Mineral Commodity Summaries[2]

Commodity	Net import reliance as a percentage of apparent consumption in 2023	Leading import sources (2019–22)[2]
ARSENIC, all forms	100	China,[3] Morocco, Malaysia, Belgium
ASBESTOS	100	Brazil, Russia
CESIUM	100	Germany
FLUORSPAR	100	Mexico, Vietnam, China, South Africa
GALLIUM	100	Japan, China, Germany, Canada
GRAPHITE (NATURAL)	100	China,[3] Mexico, Canada, Madagascar
INDIUM	100	Republic of Korea, Canada, Belgium
MANGANESE	100	Gabon, South Africa, Australia, Georgia
MICA (NATURAL), sheet	100	China, Brazil, India, Belgium
NIOBIUM (COLUMBIUM)	100	Brazil, Canada
RUBIDIUM	100	China, Germany, Russia
SCANDIUM	100	Japan, China, Germany, Philippines
STRONTIUM	100	Mexico, Germany, China
TANTALUM	100	China,[3] Germany, Australia, Indonesia
YTTRIUM	100	China,[3] Germany, France, Republic of Korea
GEMSTONES	99	India, Israel, Belgium, South Africa
ABRASIVES, fused aluminum oxide	>95	China,[3] Canada, Brazil, Austria
NEPHELINE SYENITE	>95	Canada
RARE EARTHS,[4] compounds and metals	>95	China,[3] Malaysia, Japan, Estonia
TITANIUM, sponge metal	>95	Japan, Kazakhstan, Saudi Arabia, Ukraine
BISMUTH	94	China,[3] Republic of Korea, Belgium, Mexico
POTASH	91	Canada, Russia, Belarus
STONE (DIMENSION)	87	Brazil, China,[3] Italy, Turkey
DIAMOND (INDUSTRIAL), stones	84	India, South Africa, Russia, Congo (Kinshasa)
PLATINUM	83	South Africa, Switzerland, Germany, Belgium
ANTIMONY, metal and oxide	82	China,[3] Belgium, India, Bolivia
ZINC, refined	77	Canada, Mexico, Peru, Republic of Korea
BARITE	>75	India, China,[3] Morocco, Mexico
BAUXITE	>75	Jamaica, Turkey, Guyana, Australia
IRON OXIDE PIGMENTS, natural and synthetic	75	China,[3] Germany, Brazil, Canada
TITANIUM MINERAL CONCENTRATES	75	South Africa, Madagascar, Australia, Canada
CHROMIUM, all forms	74	South Africa, Kazakhstan, Russia, Canada
PEAT	74	Canada
TIN, refined	74	Peru, Bolivia, Indonesia, Malaysia
ABRASIVES, silicon carbide	73	China,[3] Brazil, Canada, Netherlands
SILVER	69	Mexico, Canada, Poland, Switzerland
COBALT	67	Norway, Canada, Finland, Japan
GARNET (INDUSTRIAL)	67	South Africa, Australia, China,[3] India
RHENIUM	60	Chile, Canada, Germany, Kazakhstan
ALUMINA	59	Brazil, Australia, Jamaica, Canada
VANADIUM	58	Canada, Brazil, Austria, Russia
NICKEL	57	Canada, Norway, Finland, Russia
DIAMOND (INDUSTRIAL), bort, grit, and dust and powder	56	China,[3] Republic of Korea, Ireland, Russia
MAGNESIUM COMPOUNDS	52	China,[3] Israel, Canada, Brazil
GERMANIUM	>50	Belgium, China, Canada
IODINE	>50	Chile, Japan
MAGNESIUM METAL	>50	Canada, China,[3] Israel, Taiwan
SELENIUM	>50	Philippines, Mexico, Germany, Canada
TUNGSTEN	>50	China,[3] Germany, Bolivia, Vietnam
SILICON, metal and ferrosilicon	<50	Brazil, Russia, Canada, Norway
COPPER, refined	46	Chile, Canada, Mexico
ALUMINUM	44	Canada, United Arab Emirates, Bahrain, Russia
PALLADIUM	37	Russia, South Africa, Italy, Canada
LEAD, refined	35	Canada, Mexico, Republic of Korea, Australia
MICA (NATURAL), scrap and flake	28	China, Canada, India, Finland
PERLITE	26	Greece, China, Mexico
LITHIUM	>25	Argentina, Chile, China, Russia
TELLURIUM	>25	Canada, Germany, Philippines, Japan
SALT	25	Canada, Chile, Mexico, Egypt
BROMINE	<25	Israel, Jordan, China[3]
ZIRCONIUM, ores and concentrates	<25	South Africa, Australia, Senegal, Russia
CEMENT	22	Turkey, Canada, Greece, Mexico
VERMICULITE	20	South Africa, Brazil, Zimbabwe

Figure 2. Examples of Secondary and Unconventional Feedstocks

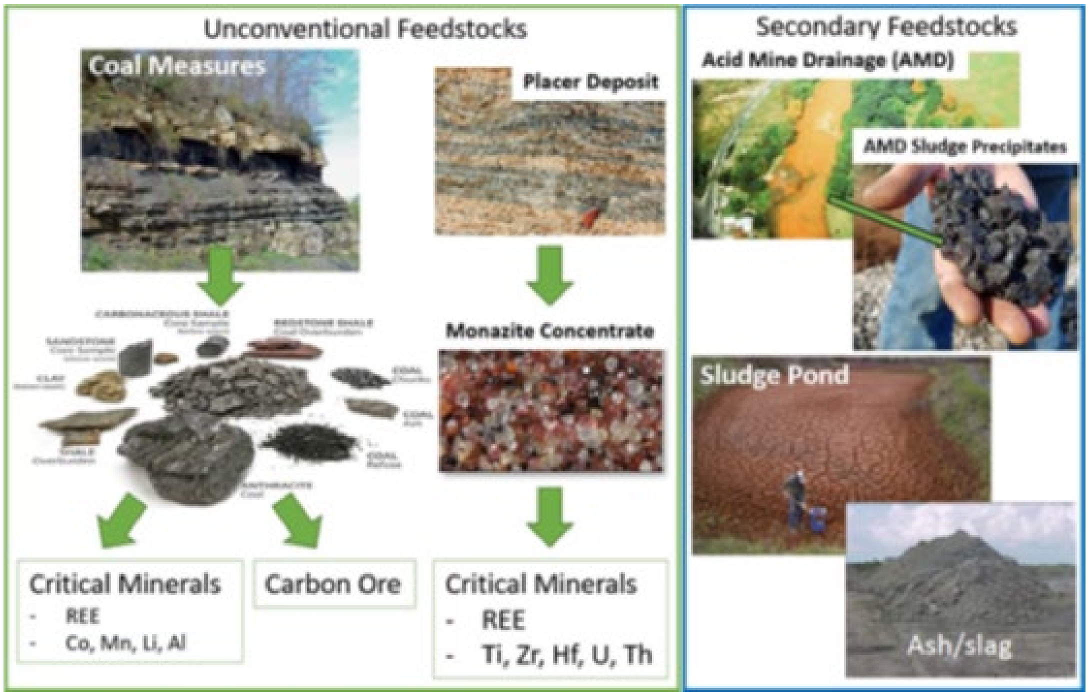


Table 1. Critical Mineral and Carbon Ore Feedstocks

	Unconventional	Secondary
Rock and Sediment Extraction Sources	• Critical mineral-rich: Underclays, coal, shale, garnet sands, sulfide mineral byproducts (Co, Sb, platinum group elements (PGEs), Sc, Se), seawater (Li), produced waters • Carbon-rich: coal	• Critical mineral-rich: overburden, tailings/ refuse, sludge, acid mine drainage • Carbon-rich: coal mine tailings
Mineral Processing, Extractive Metallurgy, and Manufacturing Sources[7]	Critical mineral-rich: Mineral processing tailings, slag and furnace residue, hydrometallurgical leachates.	Critical mineral-rich: Coal fly ash, flume dust, slurry, cakes, wastewaters and acid solutions, alloy residues.

FECM's Division of Minerals Sustainability (DMS) has shown that coal refuse, coal byproducts, and other coal-related waste streams, such as acid mine drainage, have usable concentrations of CMMs; for example, coal ash impoundments typically contain more than 470 parts per million (ppm) rare earth elements and yttrium, many with specific relative enrichments in the most critical heavy REE as compared to conventional ore deposits. Initial rough estimates suggest that such sources currently contain more than 10 million tons of REEs[8] and tens of billions of tons of carbon ore, if it can be produced economically. And while annual coal production has decreased from a high of over 1,000 million short tons (0.907 million metric tons) in 2008 to about 535 million short tons (485 million metric tons) in 2020, recently it has remained steady at around 594 million short tons (539 million metric tons)[9] in 2022. At 2022 production levels, it can be roughly estimated that over 30,000 metric tons of REEs and over 600,000 metric tons of non-REE critical elements are contained in produced coals.

Circularity within the Department of Energy

A circular supply chain emphasizes six Rs: Recover, Reuse, Remanufacture, Recycle, Redesign, and Reduce. * One example of how such concepts are employed throughout DOE offices is the following:

- Office of Advanced Research Projects Agency- Energy (ARPA-E) – The Mining Incineration Disposal Ash Streams (MIDAS) topic focuses on recovering critical materials from waste-to-energy (WTE) plants. Advances in WTE technology provide opportunities to recover discarded critical materials (often from electronic waste) while producing electricity from incinerating waste.

(*) Manavalan, E., and Jayakrishna, K., (2019)

To date, FECM's research and development (R&D) program activities for CMM production have demonstrated successful recovery of CMMs from numerous abundant unconventional and secondary sources. Researchers have identified localities across the United States where coal by-products yield concentrations of rare earth elements[10] deemed to be economically producible should the need arise (e.g., due to international supply disruption). Several technologies for using coal-based and other unconventional and secondary sources as the basis for quickly increasing domestic CMM production[11] have been developed and validated at some scale. The R&D program has identified opportunities for creating new CMM supply chains through upgrades to feedstock extraction,[12] concentration, extractive metallurgy, reduction, and alloying. This includes four pilot-scale REE separation facilities that are producing kilograms of high-purity (~98%) mixed rare earth oxides (MREO). It also includes the pre-FEED studies for facilities designed to produce 1-3 metric tons/day of high-purity MREO, and several follow-on FEED studies for the same. With recent funding from the Bipartisan Infrastructure Law (BIL), it is expected that at least one demonstration facility will be built to extract, refine, and metallize, REE and associated critical minerals and materials (CMMs) from coal related feedstocks.

Producing high-purity CMM and/or high-value carbon products from unconventional and secondary sources also has the potential to support traditional energy communities by (re)building a coal and mineral processing workforce and restoring land from adverse past practices involving mining waste products. As the Program has matured, FECM has broadened the focus beyond coal-based sources to other sources, like oil and gas produced waters, phosphate process wastes, aluminum residues, carbon ores for graphite, and tailings from active domestic mines. Additionally, the Program has broadened its focus beyond REEs to other critical materials, particularly the ones on DOE's Critical Materials List like graphite, lithium, and cobalt.[13] FECM will look for opportunities to more rapidly stand up CMM supply chains for energy technology applications from a range of secondary and unconventional sources.

While a major focus will remain on coal-based feedstocks and REE recovery, these DMS investments has been building unique R&D capabilities within the U.S. government to develop transformative technologies for extracting and processing minerals from abundant low-grade domestic resources. After a decade of congressionally directed efforts targeting fossil energy systems, these investments have primed the pump for R&D related to domestic conventional ores. FECM's applied energy research lab, the National Energy Technology Laboratory contains facilities and capabilities that were transferred from the U.S. Bureau of Mines to the US Department of Energy. These facilities are well-suited to support upstream and midstream mineral recovery efforts. Leveraging these investments, DMS has begun to restart the early-stage mining innovation engines necessary to accelerate mineral resource development across the U.S.

This Multi-Year Program Plan (Program Plan) summarizes FECM's Division of Minerals Sustainability plans to evaluate and address issues that enable the creation of robust domestic supply chains. Resolving these issues requires innovative approaches that link upstream activities, midstream refining, and downstream customization to strengthen a domestic supply chain. This work brings together industry, not-for-profit entities, research organizations, and institutions of higher education to identify challenges, catalyze innovations, and develop cutting-edge rapid characterization methods, and advanced extraction, processing, and metallurgical technologies. Further, the Division of Minerals Sustainability is focused on an approach that improves productivity and international competitiveness in the extractive and associated carbon manufacturing industries while making sustainability and safety core values.

1.2 Alignment with DOE and FECM Plans

DOE's overall mission in this arena is to ensure abundant supplies of critical materials from responsible sources to protect U.S. national security and to support the manufacture and buildout of key energy and industrial technologies and infrastructure.

As shown in Figure 3, DOE's four primary research and development (R&D) priorities related to critical minerals are: (1) diversifying and expanding supply, (2) developing alternatives, (3) Improving material and manufacturing efficiency and (4) building a circular economy. Additionally, crosscutting efforts are critical to accelerate the work and solidify the impact of DOE's CMM research, development, and demonstration efforts, such as developing strong international standards for critical material supply chains, performing robust analyses (e.g., market, LCA, TEA), applying models and machine learning approaches, and enabling and verifying mineral supply chain traceability. These priorities aid in the development of resilient, sustainable, domestic CMM supply chains to enable current and future energy technology and national security needs. Since 2014, the FECM and its national laboratory, the National Energy Technology Laboratory (NETL), have been developing technologies to diversify the domestic supply and enable the reuse of coal waste and byproducts, particularly in the manufacturing of high value carbon products.

Figure 3: DOE's Strategic Pillars for Critical Minerals & Materials R&D

FECM's CMM efforts are closely coordinated with the Office of Energy Efficiency and Renewable Energy (EERE) and the Office of Science, which have both had longstanding CMM programs. This includes EERE's Critical Materials Innovation Hub (CMI), formerly known as the Critical Materials Institute, a sustained multidisciplinary effort led by Ames Laboratory and managed by the Advanced Materials and Manufacturing Technology Office (AMMTO). In the past year, the Critical Materials Collaborative (CMC) has been established, led by FECM and EERE, to integrate CMM applied research, demonstration, and deployment efforts across DOE and the federal government, to accelerate the development of domestic critical material supply chains for the nation.[14] The CMC will operationalize interagency coordination and collaboration, while adding value for recipients of DOE funding by expanding their access to world-class expertise, capabilities, and facilities. The mission of the CMC is to accelerate DOE's critical materials applied research efforts to achieve domestic energy technology

Circular and Sustainable Supply Chains

The *circular supply chain model* is regenerative by design. It replaces the "end-of-life" concept with restoration; eliminates the use of chemicals that may impair reuse; and aims to eliminate waste through the superior design of materials, products, systems, and business models. *

Sustainability is an important aspect of the circular supply chain design and has the potential to both reduce excess waste and enhance national security. Replacing the linear supply chain (in and out) model by using discarded materials enables a future with strategic use of available domestic reserves.

(*) Ellen Macarthur Foundation report: Towards the Circular Economy, Volume 1.

manufacturing and national security goals by:

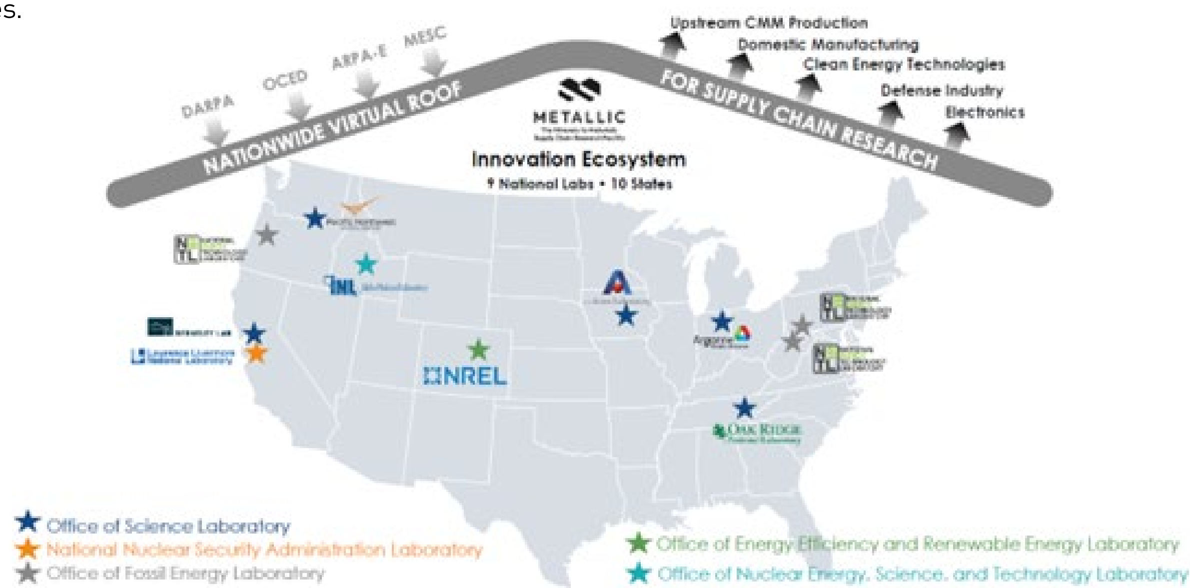
- Building a robust innovation ecosystem;
- Training critical materials leaders and the broader workforce across multiple sectors;
- Enabling industry adoption of novel, cutting-edge technology; and
- Laying the scientific and technological groundwork needed to address emerging challenges.

Additionally, DOE has performed a Critical Materials Assessment and produced a Critical Materials List.[15] As these continue to be updated, these will be used to help prioritize efforts within FECM on critical materials recovery and processing.

Guided by DOE's CMM Program and the FECM Strategic Vision, the Division of Minerals Sustainability focuses on the upstream and midstream aspects of critical materials for all supply chains, and upstream, midstream, and downstream manufacturing for carbon products. The Division supports all four of the DOE's CMM research pillars (Figure 3)—especially diversifying supply, building a circular economy, and improving efficiency—as well as much of the crosscutting and enabling capabilities, with a particular focus on standards development. The Division of Minerals Sustainability aims to foster environmentally and economically sustainable, secure, diverse, and resilient domestic CMM and carbon ore resource recovery industry. Efforts will also be made to connect work performed elsewhere at FECM, such as produced water or carbon utilization efforts.

The Division of Minerals Sustainability, with Bipartisan Infrastructure Law funding, has recently supported an alliance of nine National Labs under the leadership of NETL. This consortium of R&D experts and facilities across CMM supply chains, METALLIC, leverages existing national assets in the DOE system toward a vertically integrated set of R&D facilities that will serve to support simultaneous derisking of mine-to-metal supply chains for domestic national and energy security (Figure 4). With a federated set of coordinating facilities and experts, the DMS is investing in the continued functions of mineral processing and metallurgical R&D necessary to secure domestic mineral resources far into the future.

Figure 4. METALLIC: Vertically integrated R&D facility for simultaneous de-risking of mine to metal scale-up activities.



Finally, starting in FY24, with support from Congress, FECM has been building off recent advances in ARPA-E, including their MINER Program, to initiate a new "Mine of the Future" program, which will advance technologies to transform mining to reduce and eliminate large open pits and substantially improve mining efficiencies. This precision extraction approach will require the development of novel technologies in drilling, geophysics, chemistry, biology, robotics, autonomous systems, artificial intelligence, beneficiation, material processing, and other fields. Over the next decade and a half, FECM will build these capabilities with an eye towards transforming the mining of critical materials for the future.

1.3 Overarching Goals and Desired Benefits of R&D Investments

This Program Plan presents the long-term vision, mission, and high-level goals of the Division of Minerals Sustainability's efforts within FECM. It is meant to catalyze industry establishment of circular domestic CMM supply chains to bolster our national security and production of key energy and industrial technologies. Technology development and the establishment of government-industry partnerships are essential throughout the entire supply chain, from upstream to downstream (i.e., from mine to product), for seamless integration of all aspects of CMM and carbon ore production. The success of program goals and timing will depend on future budget levels.

The vision and mission will build upon previous success and include active engagement through federal interagency partnerships (e.g., DOE and Department of the Interior, U.S. Department of Commerce, and U.S. Department of Defense [DOD]), State Geologic Surveys and Mining Bureaus), and government-industry/academia/technical society (public-private) partnerships, especially working with the National Laboratories, as well as forging international collaborations. These partnerships and collaborations will address policy and technology requirements to develop sustainable practices for launching and nurturing domestic resource supply chains.

The productive uses of waste material for CMM and advanced carbon products have the potential to incentivize cleanup of past and present energy, mining and industrial waste streams and environmentally damaged areas, stimulate value-added economic development and create high-wage skilled jobs, while producing the sustainable supply chains needed for national security and deployment of new energy technologies. The Division of Minerals Sustainability will develop advanced technologies to safeguard the environment while supporting DOE's mission to ensure America's security and prosperity through transformative science and technology solutions.

Vision

To catalyze an environmentally and economically sustainable critical minerals and carbon ore resource recovery industry in the United States that will support:

- Advanced defense, energy and industrial technology deployment, while adding economic value and creating high-wage domestic jobs;
- Development of secure, diverse, resilient, domestic critical minerals supply chains; and
- Environmental stewardship through co-production- and reclamation-based resource recovery and processing.

Mission

To support U.S. national security and leadership in the manufacture of defense, energy and industrial technologies by leading the federal government's efforts to:

- Characterize and assess domestic critical mineral and carbon ore resources from fossil energy-related byproducts and related resources, other secondary and unconventional feedstocks, and critical material-containing ore bodies;
- Develop advanced resource extraction, processing, and extractive metallurgical technologies; and
- Evaluate the co-production potential of critical minerals and carbon ore for high-value products.

This Program Plan was developed to encourage the formation of government-industry partnerships to rebuild domestic CMM supply chains in a manner that addresses the issues raised above. It also emphasizes partnerships with like-minded countries to support environmentally and socially responsible resource practices throughout the minerals supply chain—including mining, processing, trading and sales, worker safety, consumer safety, environmental conservation and governance.

2. Technical Plan

To develop a circular CMM supply chain, it is essential to address issues across the entire supply chain—from characterization to extraction, separations, and refining to manufacturing, consumption, and finally to recycling. In developing this Program Plan, the Division of Minerals Sustainability focused its efforts on the following four technical program areas and a collection of crosscutting development efforts.

- **Program Area 1 - Resource Characterization and Technology Development**: Create new methodologies, tools, and technologies required to accelerate and improve the prospecting, identification, and assessment of secondary and unconventional mineral resource quality (e.g., composition and impurities) and quantities of critical minerals and carbon ore. These abundant but low-grade domestic resources are sufficient to provide long-term and stable commercial production of domestic commodities. And such tools and technologies will help enable a much stronger ability to assess and target the development of the most promising potential secondary and unconventional resources and resource types.
- **Program Area 2 – Critical Mineral Processing**: Increase productivity for CMM extraction and concentration from unconventional and secondary sources and promote environmental stewardship through maximizing productive use of materials and reduction of residuals. Includes novel innovations in subsurface resource extraction using in situ mining and recovery of CMM as well as the use of conventional separation and refining processes. This research will advance environmentally benign and economically viable extractive metallurgy, separation, and reduction and alloying techniques and technologies to produce high-purity CMM, including rare earth metals. Technology development for recovered CMM will advance the efficiency and environmental practices for processing, metal extraction, separation, and refining of CMM from unconventional and secondary sources, expanding these products into new markets.
- **Program Area 3 – Carbon Ore Processing and Manufacturing**: Stimulate increased productivity for carbon ore extraction and concentration from unconventional and secondary sources and promote environmental stewardship through maximizing productive use of materials and reduction of residuals. Additional efforts will focus on developing novel strategies and technologies for producing a broad range of high-volume and high-value carbon products from carbon ore and expanding these products into new markets.
- **Program Area 4 – Advanced Critical Material Extraction Technology**: The "Mine of the Future" efforts will advance technologies to transform mining to reduce and eliminate large open pits and large underground tunnels, and substantially reduce increase the mining efficiency (ratio of waste rock to mined metal), while decreasing water use, greenhouse gas emissions, and other environmental impacts in general. This area is still in its inception and still being defined in more detail as of this writing represents an extension of program area 1-3 activities into feedstocks that are related to conventional ores and unconventional ores in oil and gas shale systems.

The four technical program areas are supported by crosscutting activities, including the following:

- **International Engagements, Standards, and Supply Chain Development**: The Division of Minerals Sustainability will engage in crosscutting activities that promote international collaboration and cooperation with organizations that address CMM and carbon ore standards (e.g., International Organization for Standardization) and trade policy that are essential to all four program areas. Development of international standards and partnerships are tools the United States can use to address the CMM supply and high-value product manufacturing challenges that the Nation is now facing.

2.1 Resource Characterization and Technology Development

2.1.1 Background

To secure domestic supplies far into the future, the U.S. must develop viable projects that are lower in grade than foreign-sourced mineral deposits that are currently on the margin of economic development. This need can be met, in part, by focusing on technical improvements in recovery approaches for potential secondary and unconventional resources that improves the domestic viability of these projects. FECM's primary R&D focus for most of the past decade has been on adding mineral production value to existing industrial practices, such as those associated with the hydrocarbon-industry (especially coal-related feedstocks and oil and gas produced waters). Other notable industrial wastes are also considered near-term sources of domestic supply because they are immediately minable and abundant, such as phosphate and bauxite residues, and tailings at active mines.

The Division of Minerals Sustainability and its partners can leverage existing public and private sector investments and ongoing R&D to support the restoration of a sustainable domestic supply of CMMs, in part from secondary and unconventional feedstocks. The first step is evaluating the potential to recover critical minerals and materials, including carbon, from such feedstocks. Of special importance will be engagement with the Department of the Interior (i.e., U.S. Geological Survey (USGS), Office of Surface Mining Reclamation and Enforcement [OSMRE]) and the U.S. Environmental Protection Agency (EPA).

Work by the Division of Minerals Sustainability pertaining to *Resource Characterization and Technology Development* is focused on two key areas, as outlined below:

- **Characterization of CMM and Carbon Ore Opportunities**: Research activities in this area focus on three interconnected scales: sample/core, outcrop/field, and regional characterization activities. The power of this approach lies in the interplay between the characterization technologies at all three scales to develop a regional and national inventory for CMM and carbon ore resources from unconventional and secondary sources. Efforts focus on developing and applying novel technologies, developing standardized protocols and best practices for laboratory and field methods, and determining the CMM and carbon ore resource potential.
- **Resource Prospectivity and Predictive Capabilities**: Research within this area focuses on developing robust approaches (e.g., Artificial Intelligence/Machine Learning [AI/ML] resource models) that seamlessly integrate sample and field characterization results; to accelerate the discovery of location, concentration, and value of selected CMM in unconventional and secondary sources.

Success in this area will depend on strong collaborative partnerships with other federal and state government agencies (e.g., USGS, Academia, and State Geologic Surveys).

2.1.2 Novel Technology Development

To address the expansion of the list of potential CMM sources and the associated carbon ore, as well as to reduce costs for resource characterization and recovery, the following pathways have been identified:

- Characterization Opportunities: An interconnected approach to develop and inventory U.S. unconventional and secondary resources. This requires the following: Standardized strategies (i.e., laboratory and field protocols) and technologies necessary to identify, characterize, and assess the potential CMM and carbon ore content of unconventional and secondary sources within a given material, field, or region.
    - Advanced characterization instrumentation, which is essential to expand the source of CMMs. The use of innovative, field-ready, handheld analytical instruments (e.g., XRF, LIBS, and Raman) will reduce costs for exploration, allow for rapid collection, and advance CMM and associated carbon ore resource prediction and assessment.
    - Integration of multiple technologies such as geophysical (i.e., seismic, magnetic, and gravity) surveys, LiDAR and aerial imagery, and digital bore hole and core logging systems.
    - Field exploration supported through the development of a standardized protocol and best practices for utilizing advanced spectroscopic [e.g., X-ray Absorption Near Edge Structure (XANES), Raman, and Fourier-Transform Infrared Spectroscopy (FT-IR)], spectrometry [High Resolution – Inductively Coupled Plasma – Optical Emission Spectrometry/Mass Spectrometry (HR-ICP-OES/MS)], and spatial [Scanning Electron Microscopy (SEM), Laser Induced Breakdown Spectroscopy (LIBS), Laser Ablation – Inductively Couple Plasma – Mass Spectrometry (LA-ICP-MS)] characterization techniques.
- **Assessment and Predictive Capabilities**: Dynamic simulations are critical to provide industry with the tools and technologies to understand the resource potential of future commercial projects. This requires developing:
    - Standardized CMM and carbon ore occurrence prospectivity models with calculated uncertainty. Using AI/ML, sample and field characterization results can be seamlessly integrated into regional resource models for identifying enrichment zones for CMM resources in unconventional and secondary sources.
    - Regional and national Artificial Intelligence (AI)/Machine Learning (ML) models that integrate resource deposits and occurrence probability models that allow for rapid prediction and forecasting of the location, concentration, and value of selected CMM and/or carbon ore in unconventional and secondary feedstocks.

The national labs possess specific capabilities in advanced sensing technologies and application of modeling and machine learning approaches to characterizing secondary and unconventional resources. The DMS is building a NL coalition to bring novel technologies to bear to accelerate the characterization of such feedstocks and the associated recovery of CMM from them.

2.1.3 Regional Evaluations:

- The Carbon Ore, Rare Earth, and Critical Mineral (CORE-CM) Initiative is focused on the characterization and inventory of (1) unconventional and secondary CMM resources and (2) existing mineral supply chain infrastructure (extraction, separation, refining) that could serve future CMM supply chains. This initiative is a step toward achieving a comprehensive technological assessment of U.S. unconventional and secondary byproduct resources towards the development of domestic CMM supply chains. Quantitative regional assessments are an essential link between the resource characteristics within a region and opportunities to develop a nationwide prospectus for supply chain development. Transportation costs may impact the carbon footprint of any commodity.
- The CORE-CM Initiative is designed as a multi-year effort to benefit regional economic growth and job creation while accelerating the development of upstream and midstream CM supply chain, and impacting the downstream manufacturing of high-value, nonfuel, carbon-based products.

2.1.4 Milestones

Key Milestones and Deliverables for this research focus include the following:

- Identify priority CMMs to focus on in the near term to enable the growth of key energy technologies.
- Identify standard methodologies (in collaboration with EERE, USGS, others) to quantify the resources and associated uncertainty that are available from a wide variety of domestic and North American unconventional and secondary sources.
- Develop methods, approaches, and a computational toolset with predictive model to substantially accelerate the ability to evaluate resource content of major unconventional and secondary feedstocks, incorporating primary challenges, characteristics, and opportunities.
- Produce and maintain a federated database for unconventional and secondary resources that incorporates data from many federal, state, and tribal resources.
- Identify sufficient resources to supply half of the U.S. critical mineral domestic demand by 2035 and beyond.
- Produce a national prospectus that will demonstrate the potential to fill national REE and other CMM needs for the Nation's future.
- Publication of Best Practices manuals or similar documents for unconventional CMM resource characterization, infrastructure assessment, and environmental justice developed with input from CORE-CM working groups.
- Demonstrate predictability of the quantifiable domestic unconventional and secondary CMM resources including sufficient quantities of REEs.

2.2 Critical Mineral Processing

2.2.1 Background

Existing U.S. mineral processing and smelting facilities are not adequate to meet current and future demands for energy technology manufacturing. Many of these functions have been offshored. For example, in just 2016, several domestic metal mines and mineral processing facilities were idled or closed permanently.

The intent of this program area is to support research initiatives that lead to environmentally benign, efficient, and cost-effective technologies for the extraction, separation, processing, and/or reduction to metals, of CMM and REE from unconventional and secondary sources for use in supply chain manufacturing applications. Research engagements with intermediate and/or end-product supply chain manufacturers can facilitate the validation of products produced from unconventional and secondary sources and integrating them into the supply chain. Because FECM efforts represent only a fraction of the overall R&D work for supply chains across the federal government, it is of special importance to engage with other offices within DOE, such as EERE, along with external agencies like DOD, to coordinate research, demonstration, and deployment efforts, share information on novel processing technologies, and create synergies that will accelerate the development of domestic supply chains.

Demonstrated Feasibility of Producing High Quality REE

Since 2014, bench-scale extramural research and first-of-a-kind small-scale pilot facilities have demonstrated the technical feasibility of producing small quantities of high-purity mixed rare earth oxides (MREO) and/or mixed rare earth salts (MRES). Recent achievements include the design, construction, and operation of four small pilot-scale facilities producing ~100 g/day of >90 - 98% high-purity MREO and MRES from acid mine drainage (AMD), refuse, fly ash, and lignite coals using conventional separation and recovery processes.

2.2.1 Commercialization of Conventional Technologies R&D Track

- **Individual Separation and Reduction to Metals**: Research will (1) address limitations of current conventional technologies (e.g., solvent extraction) used to produce individual REE and/or CMM from high-purity mixed concentrates with subsequent conversion to metals or binary metals, and (2) develop novel processes for individual RE separation and reduction to metals that have potential for 20% lower capital and operational expenditure costs than current conventional standard practice.
- **Enable Commercial Production**: Research will identify innovative, scalable pathways spanning process stages from separation to final reduction to improve productivity, reduce costs, and lessen environmental impacts. This includes developing concepts to improve the purity and quantity of economically produced CMM and REE.

The development and validation of innovative technologies for processing will maximize the production potential of CMM to decrease risk of projects to market volatility. Design strategies for process integration and processing facilities that can minimize processing steps and chemicals needed for REE, CMM and carbon ore recovery will decrease process system capital and operational expenditures.

While early-stage technologies show great long-term potential for transforming the mineral processing industries, it is also critically important to bring toward commercialization technologies that have more potential to be cost-effective and environmentally friendly in the near term. FECM has dedicated significant resources towards moving more conventional technologies from smaller scales closer to commercial scale to enable earlier adoption, enabling the possibility of building key pieces of a domestic processing industry to be ready for more transformational technologies that will appear in the long run.

Since 2014, bench-scale extramural research and first-of-its-kind small-scale pilot facilities have demonstrated the technical feasibility of producing small quantities of high-purity mixed rare earth oxides (MREO) and/or mixed rare earth salts (MRES). Recent achievements include the design, construction, and operation of four small pilot-scale facilities producing ~100 g/day of >90 - 98% high-purity MREO and MRES from acid mine drainage (AMD), refuse, fly ash, and lignite coals using conventional separation and recovery processes. These facilities were assessed during conventional separation processes for near-future production goals of 1-3 metric tons/day of high-purity MREO/MRES.

Extramural research activities in this area are focused on scale-up to larger-scale pilot/demonstration projects, capable of producing 30-100 metric tons MREO and MRES per year, to demonstration/near commercial projects that can produce 1-3 metric tons/day MREO and MRES—all with the capability to perform individual, high-purity separations and reduction to metals.

2.2.2 Advanced Separations & Processing Technology (improvements to existing and tested technologies)

The goal in this area is to improve the overall recovery and purity of CMM and individually separated, high-purity (ISHP) rare earth oxides (REO) and/or rare earth salts (RES). R&D is developing advanced, environmentally benign, reduced cost, ISHP and reduction to metal concepts. R&D efforts will be performed in conjunction with intermediate and/or end-product supply chain manufacturers as R&D team members, thus enabling production and supply of REE and CMM from unconventional and secondary sources to commercial or defense products. FECM will especially look for opportunities to partner with other agencies, such as the DOD, in this area.

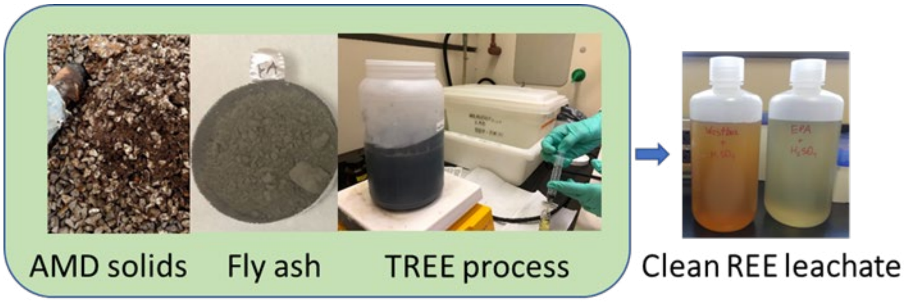
2.2.3 Next Generation Processing Technologies

CMM supply chain optimization requires application of cutting-edge extraction, concentrating, and processing technologies to maximize resource recovery while demonstrating reduced risk and improved environmental and economic performance. FECM is providing the research pathways for commercial production of REE and other CMM metals in the following three key areas:

- **Innovative Technology Development**. Innovative intramural technologies will continue to be developed and will need further validation. These technologies will span processing and separation to improve productivity, reduce costs, and lessen any potential environmental impacts. Research in this area would include lab/bench-scale activities:
    - Develop and validate concepts at lab/bench-scale (TRL 3–4; Figure 5) for innovative pathways that build from basic, fundamental R&D, such as approaches developed in the Office of Science, NSF, or ARPA-E. Results from testing will be used to prepare technoeconomic assessments comparing existing processing systems with innovative technology substitutes.

  - Identify and develop opportunities for domestic REE and other CMM production (with carbon product co-production) potential to make extraction, separation, and recovery processing more economical. Development of thermodynamic and kinetic databases with AI/ML capabilities will reduce uncertainty in the application of appropriate extraction and separation techniques for specific unconventional and secondary sources.
- **Integration of Industrial Beneficiation Methods and Technologies**. Production of highly enriched (by a factor of 5-10 from original mixture) CMM lowers the costs associated with transportation of material to processing facilities and reduces the quantity of chemicals needed for leaching. Research pathways include:
  - Identification (from surface and underground mining) and development of novel concentration methods and technologies that increase the concentration and quality of CMM and carbon ore, improve environmental performance, and enhance energy efficiency.
  - Concentration strategies that use database and associated AI/ML techniques to select appropriate concentration methodology and technologies for specific source material.
  - Integration of the co-production potential of CMM groups or of carbon ore for other high-value end products with current industrial activities.
- **Remediation of Existing Sites and Abandoned Mine Residuals**. To reduce and eliminate mine residuals it is essential to designate best practices for categorizing and prioritizing mine sites. Production of CMM and carbon ore from secondary sources has the potential to positively impact legacy environmental issues associated with mine waste. Developing strategies, risk assessment, and best practices for the reduction and elimination of mine residuals incentivizes cleanup of existing and abandoned mine sites, while providing economic and environmental benefits to disadvantaged communities. This will be accomplished through:
  - Collaboration with other Federal agencies (EPA and OSMRE) in development of assessment methodology and best practices for categorization and prioritization of mine sites and assessing environmental issues and resource concentrations.
  - Conduct outreach and community engagement to discuss the environmental and economic benefits for communities for recovery of CM and carbon ore from the processing, reduction, and elimination of mine residuals.

Figure 5. Targeted Rare Earth Extraction (TREE), a novel process developed at NETL for the extraction of REE, Sc, and Co from AMD solids and Powder River Basin Fly Ash.[16]



2.2.4 Milestones

Key Milestones and Deliverables for this research focus include:

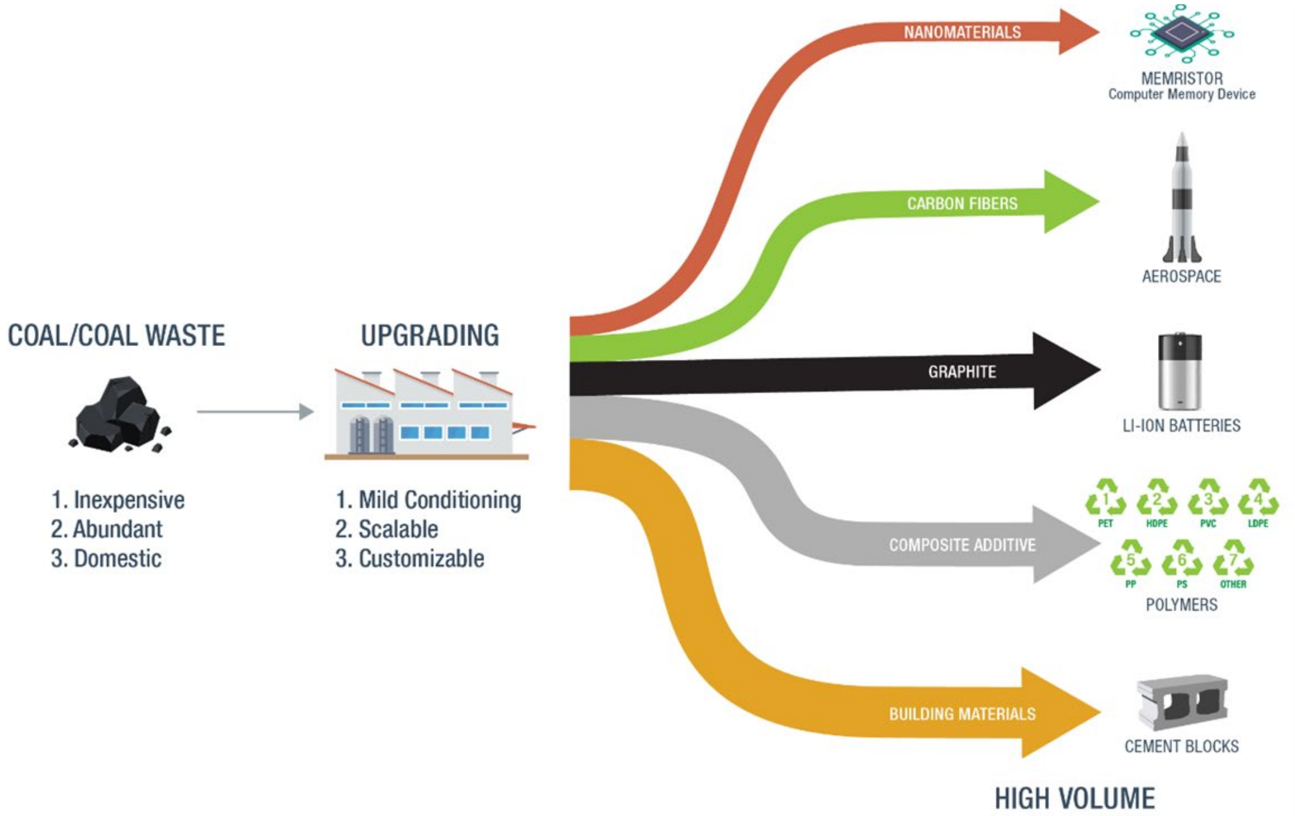
- Identify a multicriteria evaluation/prospecting method for chemical extraction from each feedstock (of interest).
- Develop risk assessment/management methodology/matrix to evaluate remediation/beneficiation opportunities (with USGS, EPA).
- Operation of large pilot to demonstration-scale facilities that can produce at least 30 metric tons per year (ideally 1-3 metric tons/day) MREO and MRES as well as co-produce CMM and other primary products.
- Successfully incorporate extraction technology into pilot facility(s) that will generate at least 30 t/yr REE and other CMM.
- Identify and develop best practices for first generation multicriteria evaluation/ optimization and risk assessment for extraction methods.
- Develop multiple transformational (next generation) extraction technologies that improve performance across multiple criteria (especially green chemistry).
- Implement transformational extraction technologies in pilot scale extraction and processing facility(s)

2.3 Carbon Ore Processing and Manufacturing Technology

Coal has been a critical domestic resource, contributing to U.S. economic growth since the 19th century. However, in a shifting energy generation paradigm to low carbon energy, technology innovation is helping extract the full economic value from the carbon ore within this versatile domestic resource. Research efforts by the Division of Minerals Sustainability are focused on developing novel strategies and technologies for producing a broad range of high-value carbon products from carbon ore and expanding these products into new markets. Special focus will be placed on ensuring that processing and manufacturing technologies are safe for workers and all products are safe for end users, to reduce barriers to market adoption.

The overall goal with respect to carbon ore processing is to support R&D capable of transforming coal and carbonaceous coal wastes into value added materials, exclusive of well-established thermal (power) and metallurgical (coke) markets. As illustrated below in Figure 6, the DMS supports R&D across the entire value spectrum, ranging from high-volume through high-value.

Figure 6. Carbon Ore Processing Program Value Spectrum



Support for this broad spectrum of technologies is reflective of the fact that the DMS is not exclusively supporting technologies that can replace the overall gross demand for coal, but also the economic impact (i.e., effect on GDP) associated with higher value uses of the resource. The following sections will discuss the general challenges faced by the program, as well as the technical plan for addressing these challenges within specific research areas supported by the program.

2.3.1 General Challenges

From the perspective of utilizing coal and carbonaceous coal wastes to create value-added products, these are the challenges that are common amongst the various research thrusts.

- **Feedstock Variability and Complexity.** The term coal is an inexact descriptor for a complex hydrocarbon with variable structure and composition. Even if coal is further classified by rank, there still exists variability from region to region and even seam to seam. Furthermore, as coal is concentrated plant matter, it can contain most of the elements within the periodic table to varying degrees. The variability and complexity of coal's molecular structure may require that processing conditions (or even processing methods) are tailored to the source coal or carbonaceous coal waste resource. It is necessary to address this problem by either ensuring that there is enough source coal for the application identified or demonstrating a technology on multiple coals. This problem could be exacerbated when examining coal waste resources—high carbon refuse from early-stage preparation plant technology would vary not only based on the source coal but also based on the technology that was initially used to clean it.

- **Competing Hydrocarbon Resources**. Coal is the least expensive form of carbon, but it is not optimal for all applications. An illustrative example is liquid fuels; while these can and have been produced from coal, it is typically more economical to begin with a liquid hydrocarbon resource such as crude oil. It is also the case that gaseous hydrocarbon feedstocks are often the preferred starting point for certain carbon products, especially those that are highly saturated (i.e. high hydrogen to carbon ratio). For these reasons, the focus is primarily on products that have lower hydrogen-to-carbon ratios and those with long-range (graphitic) order, as coal structure is well suited to this class of carbon products.
- **Environment, Safety and Health (ES&H) Concerns**. The observation that coal may contain many elements of the periodic table in trace amounts raises ES&H concerns, particularly around heavy metals (e.g., arsenic, mercury, cadmium) as well as non-metals of concern (e.g., sulfur, selenium, silicon). Additionally, there could be concerns relating to volatile organic compounds (VOCs) if coal were hydrogenated or mixed with other compounds (e.g., silanes or polymers). These ES&H concerns are present during all phases of the product's life cycle; creation, use/service, and disposal. To ameliorate these concerns, ES&H analysis is required for all cooperative agreements.

Figure 7. Li-Ion batteries in 18650 form factor with coal-based anodes

2.3.2 Electrochemical Devices

The DMS supports R&D for the use of coal-derived graphite (or direct use of coal) in electrochemical devices, including Li-ion batteries and supercapacitors. The potential benefits of these technologies are multi-faceted, i.e., domestic supply, plentiful, and inexpensive. The subsections below will discuss efforts and plans in these areas.

Batteries

The DMS advances discoveries to produce a domestic supply of graphite, graphite alternatives, or hard carbons for mass-producing lithium-ion or sodium-ion batteries. Carbon is a necessary battery ingredient to support technologies such as battery electric vehicles (BEVs), energy storage systems, and consumer electronics. Experience suggests that advancements are unlikely to be pursued unless they can be demonstrated on a full Li-Ion cell in an industrially relevant form factor. For this reason, the DMS supports the development of full cell battery testing and characterization. A recent success includes the direct use of coal (combined with a ceramic forming resin) as an anode in 18650 cells, as show in Figure 7.

These cells were independently tested as the Battery Innovation Center in Indiana and won their prestigious "Voltage Award," which is an annual award presented to the one technology that has the greatest potential to advance widescale adoption of Li-Ion batteries.

In the near-term, the most vital need is to understand why coal-resin composites are working well in this application. Referencing the earlier point that coal often contains many elements from the periodic table, it would be expected that some of these constituents would harm electrochemical performance over several thousand cycles, but this has not been observed in practice. The DMS is addressing this question through Field Work Proposals with National Labs that have experience and expertise in characterizing lithium-ion cell performance and material set stability.

Supercapacitors

Supercapacitors have the benefits of extremely high-power outputs and long lifespan over a broad working temperature, but their adoption has been limited by a relatively low energy-density. The DMS supports R&D to increase energy density by tailoring the surface area, porosity/pore size distribution, microstructure, and chemistry of carbon from coal-derived sources. This work is occurring within NETL's Research and Innovation Center but will be expanded to extramural research as TRL increases and budgets allow.

2.3.3 Carbon Fibers

Coal-Derived Carbon Fibers

In general, there are two classes of carbon fibers: (1) graphitic carbon fibers which tend to have high modulus (stiffness) and conductivity (thermal and electrical) but are relatively low strength; and (2) non-graphitic fibers that have a lower modulus and poorer conductivity but are higher tensile strength. The graphitizable fibers are more costly and are generally reserved for applications where high costs are acceptable (e.g., aerospace and sporting goods) and the lower cost non-graphitizable fibers are often used in automotive applications where they are composited with polymers (e.g., fiber modified body panels). The DMS is currently supporting a series of Field Work Proposals (FWPs) with Oak Ridge National Laboratory (ORNL), where they produce carbon fibers from coal-based pitches on their pilot line (which is analogous to a pilot line that a carbon fiber manufacture might tune prior to final scale-up). Additional efforts will continue to produce both graphitizable and non-graphitizable carbon fibers from coal resources as the program moves towards scaling the technology.

Polymer Composites
The DMS has supported R&D of carbon fiber modified polymers and resins for additive manufacturing applications via FDM (fused deposition modeling) or SLA (stereolithography). The addition of carbon fiber reduces shrinkage and warping, which are failure mechanisms for additively manufactured items. Additionally, if carbon loadings are sufficient, it may be possible to produce graphitizable forms and molds, which would provide new manufacturing capabilities for rapid prototyping via metal casting.

Pitch Precursor Production
The DMS has supported R&D to investigate how coal and coal waste resources can be economically transformed into pitch precursors for carbon fiber production. Pitch chemistry affects whether resultant carbon fibers are graphitizable or non-graphitizable and affects how easily the fibers can be spun and stabilized. There are concurrent efforts to model these reactions via computation chemistry, as there are numerous classes of reactions that occur during the heat treatment of coal-based pitches. These efforts will continue in coordination with carbon fiber development efforts.

2.3.4 Building Materials
Worldwide, approximately one teratonne (1,000 gigatonnes) of building materials will be required over the next two decades.[17] Reaching this number via biomass alone is intractable, and therefore much of this demand will be met through mined materials, whether mineral (e.g., concrete) or hydrocarbon (e.g., coal, petroleum, and natural gas). Carbon materials offer both advantages in conventional building materials through the ability to decrease costs and improve performance; and the capability to enable fundamentally new construction techniques.

Decking, Roofing, and Siding
The DMS has supported R&D to produce building materials from coal and coal-wastes. Building materials produced thus far include roofing tiles, siding, and composite decking as shown in Figure 8. The composite decking example is illustrative of the benefits of coal derived building materials, as it is more than a simple substitution for a commodity product (wood flour) as it enables the displacement of a much more expensive component (high-density polyethylene). This coal-derived building material has demonstrated the capability to meet product performance standards and has been manufactured on the same equipment that manufactures commercially available composite decking.

Figure 8. Composite decking produced from HDPE and pulverized coal

The DMS will continue to support R&D into coal-derived building materials as resources allow, especially for high TRL efforts that are near commercialization. The focus will be on demonstrating the cost and performance of these composites as production scale increases.

Concrete

Graphene has shown the ability to significantly increase the strength of concrete at loadings on the order of a tenth of a percent (by weight). This is a potential early stage win for coal-derived building material modification, especially as the industry moves from proscriptive requirements to performance-based requirements in an effort to reduce carbon emissions.

2.3.5 Carbon Nanomaterials

This technical area represents a basket of different R&D supporting applications for carbon nanomaterials. A recent example includes R&D into coal-derived materials as the basis for memristors, one of only four theoretical two-terminal circuits (the others being the inductor, resistor, and capacitor). This project involved TSMC (Taiwan Semiconductor Manufacturing Company) and results were published recently in the prestigious Communications Engineering journal. The low TRL technologies may not consume significant quantities of coal or coal-waste, but they could add significant value to local and regional economies and to GDP. Research into memristors and other nano-material applications will continue. Other applications are likely to include carbon for perovskite solar photovoltaics, conductive inks, and carbon metal composites.

2.3.6 Milestones

Key Milestones and Deliverables for this research focus include:

- Develop and validate novel techniques and technologies that utilize domestic carbon ore to produce high-value building and infrastructure materials that have superior qualities. Initiate scale-up from batch to continuous production.
- Develop innovative pathways to produce carbon ore-derived, mesophase pitch precursor material for carbon fiber production.
- Demonstrate transition from batch to continuous processing of mesophase pitch.
- Develop novel, energy efficient, technologies to produce synthetic graphite and high-purity silicon metal (i.e., polysilicon) from carbon ore products.
- Identify and develop innovative carbon-ore derived substitutes and additives that meet performance metrics of commercially available products.

2.4 Advanced Critical Material Recovery Technology

Despite improvements in the mining industry over the past several decades, there is still a legacy in communities across the country of the negative impacts of mining that is holding back new mines from being built at a sufficient rate to meet expected demand. Modern mining practices continue to use large amounts of energy, water, and other resources, and produce substantial greenhouse gas (GHG) emissions. Additionally, the success rate for finding new mines is very low (1000:1), taking almost a decade or more and hundreds of millions of dollars to identify and prove a resource.

The topic is about changing the way that critical materials are mined from ores and other subsurface resources. DOE is currently in the early stages of defining this area. The general vision is to develop the technologies that transform mining, eliminate open pits and large tunnels, improve safety by keeping personnel outside of mines, and substantially reduce waste, water use, energy use, GHG emissions, and other environmental emissions. If successful, this will help develop a trained workforce, improve the image of the U.S. mining sector, and facilitate the regulatory adoption of new mineral extraction projects through data collection and information sharing. Milestones for this area will be set at a future date.

2.4.1 Mining Technology development

Several different areas of technology development are being considered, with the expectation to build off current R&D efforts in SC and NSF and test concepts up to the lab scale (TRL 3–4), eventually moving to larger scale and commercialization. RDD&D areas of interest will include, but not be limited to:

- Advanced drilling technologies
- Novel geophysical tools to improve extraction efficiency
- Digital subsurface applications (autonomous ops, robotics, real-time extraction)
- In-situ mineral extraction (e.g., bio)
- Novel mineral processing techniques

- Tailings management
- Seawater and or seafloor mining

2.4.2 Mineral traceability

Additionally, it will be imperative to prove that minerals embedded in manufactured products came from trusted, safe, responsible sources and supply networks if these novel mining technologies are to be successfully brought into the commercial space. Competition with imported materials that come from other mining and processing operations with lower environmental or human rights standards is likely to compromise RDD&D and commercialization efforts toward DOE targets for the U.S. CMM economy. To that end, this program will work with other agencies to develop the capability for mineral traceability, including using chemical forensic analysis to support ledger-based approaches to ensure and validate responsible supply networks.

2.4.3 Accelerating Exploration

The need for new reliable sources of critical minerals is going to increase at an accelerated pace for the next few decades. The current pace of exploration and characterization of new deposits, often said to take 7-10 years, needs to be shortened substantially if new discoveries are to be produced at a pace needed for expected demand. To meet such accelerated schedules, new sensing and characterization technologies will be developed, including geophysical techniques, remote sensing, real-time sensing, data analytics, and machine learning. Additionally, new data will need to be collected to help support the accelerated schedules for new potential deposits, as well as to help test new technologies that can be brought to bear to accelerate development timelines. This will include the support of new projects, similarly to how geothermal, shale gas, and other new resource development has been supported by DOE in the past.

2.5 Crosscutting Efforts

To enable several of the primary objectives of the DMS effort, it becomes useful to establish supporting, crosscutting competencies. Some, as in the case of modeling and machine learning capabilities, will help to expedite or directly improve the technologies being developed. Some, such as analysis capabilities, will help guide the direction of new efforts and evaluate the effectiveness of current activities. And others, such as standards development, will help to improve the conditions into which the technologies being developed are finally applied, using the expertise that has been built by our programs. Such activities will promote international collaboration and cooperation with organizations that address CMM and carbon product standards (e.g., International Organization for Standardization) and trade policy that are essential to all four technology areas.

2.5.1 Analysis

A strong analysis capability that includes life cycle assessment (LCA) and technoeconomic assessment (TEA), as well as market analysis, will be valuable to help guide, build, and evaluate our programs. It is also of great importance for FECM to coordinate our analysis capabilities with other offices within DOE. Coordination of these analysis activities and communicating the findings will better prepare all DOE offices in making decisions about how to allocate future resources. Additionally, as DOE's EIA gets more involved in collecting CMM data, it will substantially improve the quality of data collected and used.

As far as FECM analysis competencies are concerned, current focus is on developing and using standards for LCA and TEA that support the secondary and unconventional resources that FECM is a leader in, as well as the evaluation of upstream and midstream technologies, and the manufacturing of carbon products. Analysis capabilities will be supportive of guiding the Division in its annual planning efforts.

2.5.2 Modeling and Machine Learning

DOE possesses substantial computational power that can and should be used to help model CMM extraction processes from the molecular to commercial process scale. As more data is collected through lab and pilot scale experiments, machine learning and other AI technologies will also be used to improve speed and performance in all CMM areas.

- Data collection and curation (for AI/ML application): A key aspect of applying modeling and machine learning to any problem, including the efforts here is the collection, evaluation, quality control, and curation of data, such as that being collected by the CORE-CM efforts. Such data includes but is not limited to mineralogy and constituent analysis of potential feedstocks, thermodynamic and kinetic information, and data related to key extraction and processing technologies. A key aspect will be to collect, QA/QC, and store the data that is generated in a way that is useful to those applying models, machine learning, and especially the validation and verification thereof. It should be noted, however, that Critical Minerals and Materials is a sensitive area of research, and care needs to be made that such data is not shared inappropriately, and especially in such a way that it could damage the national or economic security of the U.S.
- Machine learning and artificial intelligence (AI/ML): AI/ML can be an extremely effective tool to develop new technology and improve efficiencies. This crosscutting area is meant to focus on the support of AI/ML tools that can support DMS efforts, including the rapid evaluation of potential secondary and unconventional resources and real-time analysis of processing inputs and outputs to support process optimization.
- PrOMMiS: The Process Optimization and Modeling for Minerals Sustainability (PrOMMiS) Initiative is a BIL-funded activity focused on transforming the national Critical Minerals, Materials and Rare Earth Elements (CMM & REE) landscape to amplify the impact of Department of Energy (DOE) investments. PrOMMiS provides a toolkit for accelerating the identification, design, scale-up, and integration of innovative CMM & REE processes through successful leveraging of the most advanced system modeling, optimization, and analysis framework (i.e., IDAES) with existing DOE expertise in CMM & REE technologies. PrOMMiS is designed to support DOE researchers, awardees of DOE funding, and industry partners to accelerate the scale-up of novel CMM & REE technologies by de-risking the development and deployment of commercial scale processes and maximizing learning throughout the development cycle.

2.5.3 Standards

US representation in international standards development is critical for the U.S. and its allies to be successful in creating manufacturing capabilities and building domestic capacity that can compete on a fair playing field. International standards developed with U.S. representation ensure all countries meeting that standard have the same quality, environmental, and labor practices. DOE will work with the EPA, NIST and other US and international organizations to ensure US interests are protected in the development of effective international standards across critical mineral and material supply chains. FECM will also work domestically with other federal agencies to develop and evaluate certification options for critical mineral supply chains to support more rapid development and implementation.

The International Organization for Standardization (ISO) Technical Committees (TC) Relevant to the Division of Minerals Sustainability Mission and Vision

ISO/TC 298 – Rare Earths: Composed of four committees that are focused on standardization in the field of rare earth mining, concentration, extraction, separation, and conversion to useful rare earth compounds/materials (including oxides, salts, metals, master alloys, etc.), which are key inputs to manufacturing and further production processing in a safe and environmentally sustainable manner. The scope of the four committees is to define vocabulary related to rare earth elements, indicate requirements for recycling of industrial waste and end-of-life products, and specify standard methodology for gravimetric and titration analyses of REE in metals and oxides. A fifth committee will be formed entitled “sustainability,” and the United States will lead this committee’s efforts to develop a standard titled “Rare Earth Sustainability: Part 1 – Mining, Separation, and Processing.”

ISO/TC 333 – Lithium: Standardization in the field of lithium mining, concentration, extraction, separation, and conversion to useful lithium compounds/materials (including oxides: salts, metals, master alloys, lithium-ion battery material, etc.). The scope of this technical committee includes terminology, technical conditions of delivery to overcome transport difficulties, and unified testing and analysis methods to improve the general quality of lithium products. The United States proposed a sustainability standard at the inaugural plenary meeting of TC333.

Source: International Organization for Standardization / US TAG ISO TC265

2.5.4 User Facilities/Test Beds

Significant investment goes into building pilot and demonstration scale facilities. As DOE helps establish such facilities, careful attention should be paid as to whether these facilities could be used to help test and implement new technologies as they are being developed. A successful example of this in a different technology area is the National Carbon Capture Center (NCCC), which was originally developed as a stand-alone project, but ended up supporting the testing and development of dozens of carbon capture and other technologies over the past 2 decades. FECM and DMS will evaluate the several large facilities being built with funding from FECM, other DOE Offices and other federal agencies (e.g., MESC, LPO, and DOD) for opportunities to create test beds, as well as opportunities to develop new test facilities.

- METALLIC: The METALLIC effort described above supports the creation of R&D facilities at multiple national labs for the development and scaling of futuristic CMM extraction, separations, processing, refining, and manufacturing technologies toward rapid commercial deployment. METALLIC will bring online several new facilities and upgrade existing facilities within the NL complex. Where possible, these facilities will be used with industry, academic, and other partners to support technology development and information sharing.

3. Engagement Outside FECM and DOE

For more than a decade, DOE has been a leader in addressing critical supply chain challenges, with the demand increasing in scope and magnitude. The Division of Minerals Sustainability is one of several DOE Offices and Divisions that are addressing CMM and REE development and deployment. As such, FECM is a co-leader (with EERE) of the Critical Minerals Collaborative (CMC), as described in section 1.3 above. The Collaborative will be a focal point for developing an innovation ecosystem around critical minerals and materials, inviting other agencies (e.g., NSF, DOD, USGS) to engage with labs, academia, industry, and more.

The Division of Minerals Sustainability is committed to collaborating with the other DOE Offices and other government agencies through the CMC and as is otherwise useful to advance the nation's CMM R&D goals. For example, DOE plays a leadership role in the National Science and Technology Council (NSTC) Critical Minerals Subcommittee, which regularly interacts with interagency partners (e.g., DOI, EPA, DOD, DOC, U.S. Department of State [DOS], National Aeronautics and Space Administration (NASA), U.S. Department of Transportation (DOT), National Science Foundation (NSF), and Department of Homeland Security [DHS]) to advise on R&D efforts and other policies relating to CMM. As such, the Division of Minerals Sustainability works with DOE colleagues to contribute to this subcommittee. Additionally, the Division of Minerals Sustainability seeks to identify strategic opportunities to collaborate with external agencies outside of the NSTC, including through the Federal Mining Dialogue.

In the future, to maintain alignment with the priorities of key stakeholders—including industry, end-users, academia, non-governmental organizations, the investment community, and other government agencies—the Division of Minerals Sustainability will continue to actively solicit input for the planning of its activities. Among the primary channels for this input are Requests for Information (RFI) and workshops conducted by DOE to help establish high-level program direction and to develop and update technology-specific RDD&D plans.

The Division of Minerals Sustainability also regularly conducts workshops for specific technology areas, to identify and update RDD&D priorities, develop plans, and identify technical targets and milestones. These workshops involve a wide range of stakeholders and provide an open forum for discussion of the status of technologies and the challenges facing their development and deployment. Results from these activities will continue to feed into the development of DOE strategies and funding plans.

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[8] U.S. Department of Energy, Report to Congress. *Report on Rare Earth Elements from Coal and Coal Byproducts*. January 2017. https://www.energy.gov/sites/prod/files/2018/01/f47/EXEC-2014-000442%20-%20for%20Conrad%20Regis%202.2.17.pdf

[9] U.S. Energy Information Administration, Annual Coal Reports. https://www.eia.gov/coal/annual/

[10] American Geological Institute, 2011, *Rare Earth Elements (REE)* – a series of fifteen metallic elements, from lanthanum to lutetium (lanthanides) and two other elements: yttrium and scandium.

[11] Critical Minerals Sustainability Program Portfolio 2020-2021. https://www.netl.doe.gov/sites/default/files/2021-05/2020-2021-REE-Portfolio.pdf

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