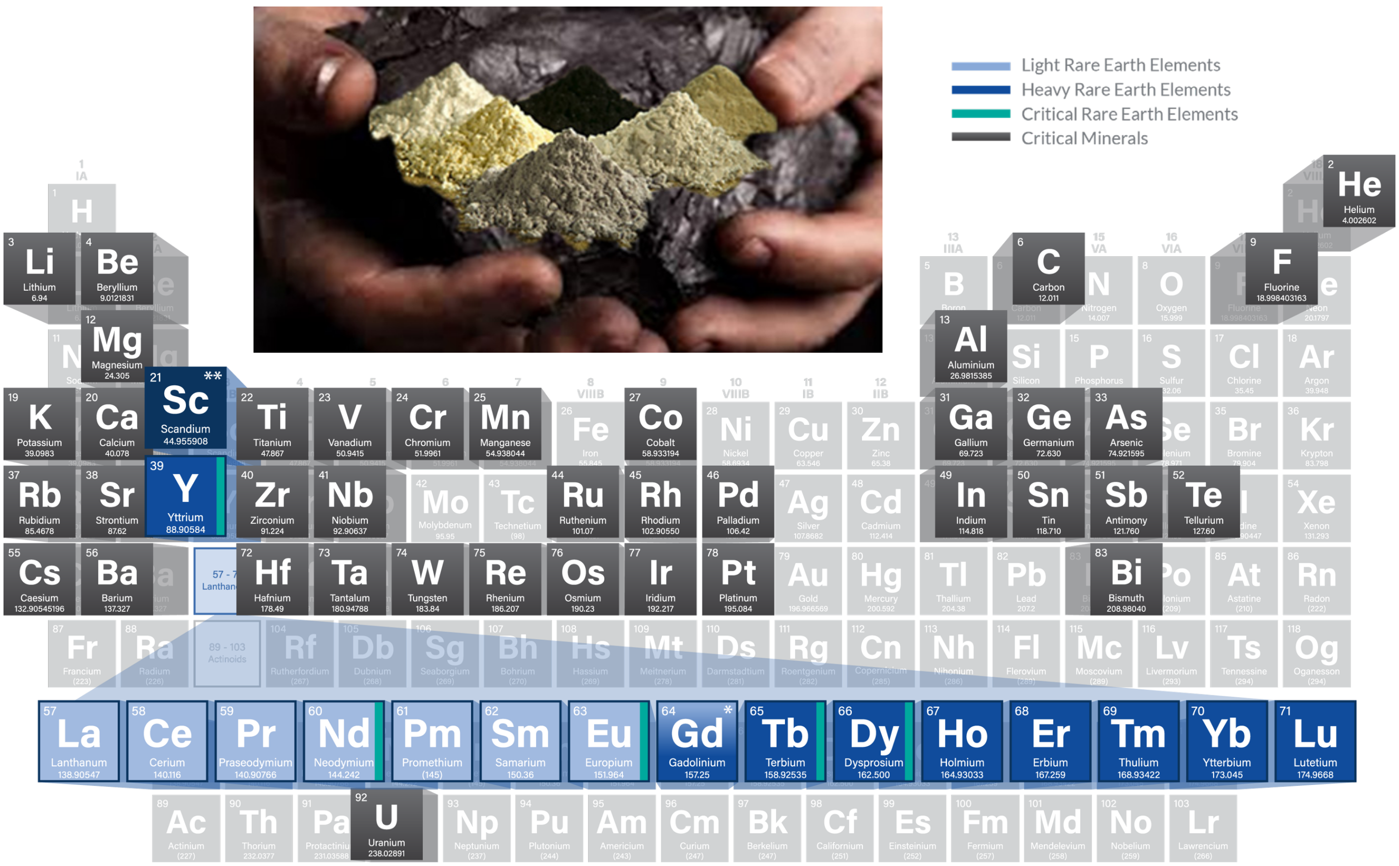
U.S. DEPARTMENT OF
ENERGY
Fossil Energy and Carbon Management

Multi-Year Program Plan for Division of Minerals Sustainability



October 2021

Multi-Year Program Plan for Division of Minerals Sustainability

United States Department of Energy
Office of Fossil Energy and Carbon Management
Division of Minerals Sustainability

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OVERVIEW

Introduction

Supply chain security for the minerals and metals needed for clean energy technology has become a strategic issue, relevant not only to climate change but to economic and national security.[1] Unfortunately, America's import dependency for many of the minerals and metals needed for clean energy—and decarbonization—has continued to increase dramatically over the past 30 years.[2]

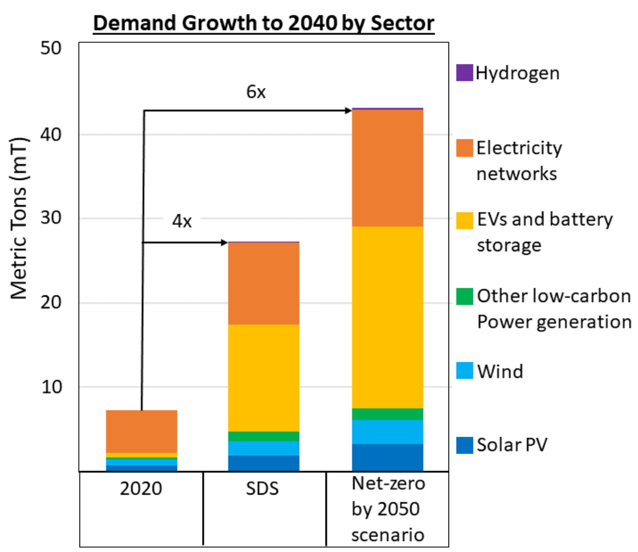


Figure 1. Mineral Demand for Clean Energy Technologies
PV: Photovoltaic; SDS: Sustainable Development Scenario

Meeting the goals of decarbonizing the economy by 2050 requires at least quadrupling mineral demand for clean energy technologies by 2040 (Figure 1)[3] – with much higher demand growth expected for some minerals, such as lithium (42x), graphite (25x), cobalt (21x), nickel (19x), and REEs (7x). However, existing domestic supplies and production for many of the minerals and metals (e.g., Co, Li, Ni, graphite, and Mn) necessary for these technologies are currently scarce to non-existent. Presently, the United States is import dependent (greater than 50% net import reliance) on 32 of the 35 critical minerals and metals, and 100% import reliant for at least 14 of these critical minerals (Table 1).[4] The number of critical minerals (CM) and metals for which the U.S. mostly or entirely relies on foreign sources for is steadily increasing.[5]

[1] Center for Strategic and International Studies Report, The Geopolitics of Critical Minerals Supply Chains. https://csis-website-prod.s3.amazonaws.com/s3fs-public/publication/210311_Nakano_Critical_Minerals.pdf?DR03x5jlrwLnNjmPDD3SZjEkGEZFEcgt.

[2] U.S. Geological Survey, Minerals Commodity Summaries 2021. https://pubs.er.usgs.gov/publication/mcs2021.

[3] International Energy Agency Report, The Role of Critical Minerals in Clean Energy Transition. https://iea.blob.core.windows.net/assets/24d5dfbb-a77a-4647-abcc-667867207f74/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf.

[4] Executive Order 14017 (February 24, 2021) required the Department of the Interior to review and update the list of 35 minerals and metals designated as critical.

[5] Department of the Interior, *Final List of Critical Minerals 2018* (Federal Register, May 18, 2018). https://www.federalregister.gov/documents/2018/05/18/2018-10667/final-list-of-critical-minerals-2018.

Table 1. U.S. Net Import Reliance of Critical Mineral Commodities Greater than 50%

Commodity	% Import	Source	Unit Cost	Import Amount (MT)	Average Import Value
Arsenic	100	China, Morocco, Belgium	$0.62/kilogram (kg)	10,500	$6,510,000
Cesium	100	Canada	$85/gram (g)	NA	NA
Fluorspar	100	Mexico, China, So. Africa, Vietnam	$160/ton (t)	390,000	$68,800,000
Gallium	100	China, Germany, UK, Ukraine	$370/kg	200	$72,500,000
Graphite (natural)	100	China, Mexico, Canada, Brazil	$1,790/t	41,000	$80,900,000
Indium	100	Canada, China, France, South Korea	$275/t	100	$30,000
Manganese	100	So. Africa, Gabon, Australia	$4.72/t	790,000	$3,730,000
Niobium (Columbium)	100	Brazil, Canada, Russia	$24/kg	7,500	$180,000,000
Rare Earths (Lanthanides)	100	China, Estonia, France, Japan	$139/kg	7,300	$1,020,000,000
Rubidium	100	Canada	$89/g	NA	NA
Scandium	100	China	$0.1-300/kg	NA	NA
Strontium	100	Mexico, Germany, China	$66/t	5,100	$370,000
Tantalum	100	Brazil, Rwanda, Australia, Canada	$158/kg	1,300	$205,400,000
Yttrium	100	China, Korea, Japan, Germany	$30/kg	600	$18,000,000
Vanadium	96	Czechia, Austria, Canada	$6.70/pound (lb)	5,000	$73,900,000
Tellurium	>95	Canada, China, Germany	$55/kg	7	$390,000
Bismuth	94	China, Belgium, Peru	$2.70/lb	2,000	$1,190,000,000
Potash	90	Canada, Russia, Israel, Chile	$665/t	5,100,000	$3,740,000,000
Titanium mineral concentrates	88	So. Africa, Australia, Canada	$1000/t	780,000	$780,000,000
Antimony (oxide)	81	China, Belgium, Bolivia	$4/lb	19,600	$157,000,000
Platinum	79	So. Africa, Germany, UK, Russia	$850/ounce	60	$2,120,000
Cobalt	76	Norway, China, Japan, Finland	$16/lb	10,000	$320,000,000
Rhenium	76	Chile, Belgium, Germany, Poland	$1,100/kg	24	$26,400,000
Barite	>75	China, India, Mexico, Morocco	$180/t	1,555,000	$309,000,000
Bauxite (Aluminum)	>75	Jamaica, Brazil, Guinea, Guyana	$27/t	3,900,000	$221,000,000
Chromium	75	So. Africa, Kazakhstan, Russia	$2,470/t	650,000	$1,770,000,000
Tin	75	Peru, Indonesia, Malaysia, Bolivia	$780/lb	55,700	$95,800,000
Magnesium compounds	54	China, Canada, Australia, Brazil	NA	480,000	NA
Germanium	>50	China, Belgium, Russian, Germany	$870/kg	26	$22,600,000
Lithium	>50	Chile, Argentina, China	$8,000/t	2,900	$23,200,000
Titanium (sponge)	>50	Japan, China, Kazakhstan	$6.90/kg	24,000	$166,000,000
Tungsten	>50	China, Canada, Bolivia, Germany	$270/t	11,000	$2,970,000
			Total	**~13,800,000**	**~$10,600,000,000**

Source: U.S. Geological Survey (USGS)

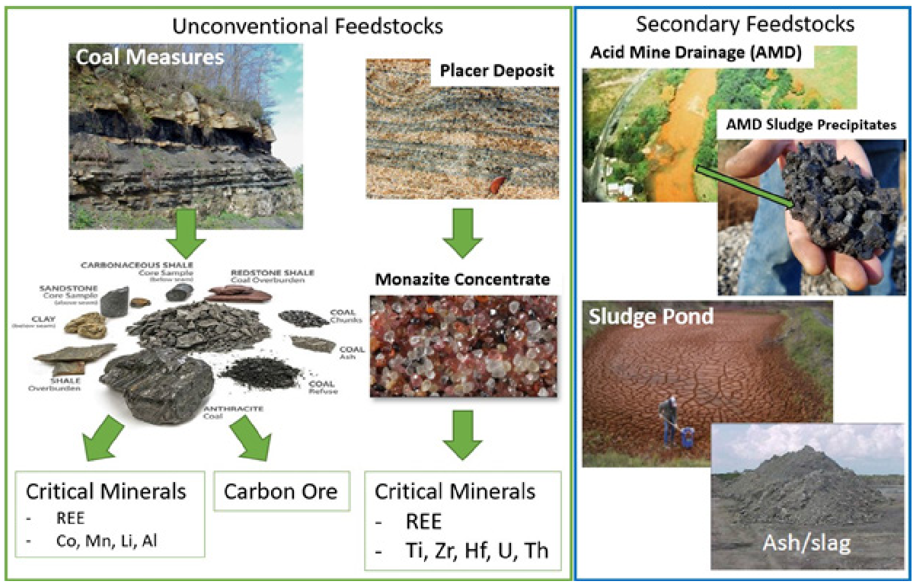
Note: commodity unit cost, amount of imports, and average dollar value are approximate based on available import data. Some data is unavailable or withheld from the public. Source: USGS and others.

MT = Metric Ton

Coal refuse, coal byproducts, and other coal-related waste streams, such as acid mine drainage, have been shown to have usable concentrations of CM; for example, coal ash impoundments typically contain more than 470 parts per million (ppm) rare earth elements (REE) and Yttrium. Initial rough estimates suggest that such sources currently contain more than 10 million tons of REE[6] and tens of billions of tons of carbon ore, if it can be produced economically. Annual coal production has decreased from a high of over 1,000 million short tons in 2008 to about 535 million short tons[7] in 2020. At 2020 production levels, it can be roughly estimated that over 30,000 tons of REE[8] and over 600,000 tons of non-REE critical elements[9] are contained in the produced coals. Typically, 80-90% of domestic coal produced is used in the power sector, with significant portions of REE and CM remaining in coal waste and byproducts (e.g., coal ash). Recent market analyses suggest[10] a potential need for more than 24 million metric tons of carbon ore from coal in 2050 for products with a market value of more than $50 billion.

Developing domestic CM supply chains for meeting current and future demand has become a national priority.[11] Development of resilient circular CM supply chains from unconventional and secondary sources (Figure 2 and Table 2) has the potential to: (1) accelerate the production of critical minerals while addressing environmental waste and degradation, (2) revitalize domestic manufacturing and refining capabilities, and (3) create new jobs in the critical mineral, metallurgical, and environmental sectors—especially in some regions being heavily impacted by the energy transition.

Figure 2. Examples of Unconventional and Secondary Feedstocks



[6] U.S. Department of Energy. Report to Congress. Report on Rare Earth Elements from Coal and Coal Byproducts. January 2017. EXEC-2014-000442 - for Conrad Regis 2.2.17.pdf.

[7] Executive Order No. 14017, 86 Fed. Reg. 11849 (March 1, 2021). https://www.federalregister.gov/documents/2021/03/01/2021-04280/americas-supply-chains.

[8] Unconventional feedstocks are natural resources that require greater than industry-standard levels of technology or investment to be recovered. Resources may become economical through co-production of more than one mineral or metal from the feedstock. Source: Unconventional Petroleum Resources – Geoscience Australia. https://www.ga.gov.au/scientific-topics/energy/resources/petroleum-resources/unconventional-resources.

[9] Secondary resources are obtained from the recovery of waste products. Source: U.S. Congressional Research Service, *Critical Minerals and U.S. Public Policy*, R45810 (Washington, D.C. June 28, 2019).

[10] NETL preliminary market analysis on Carbon Ore (2021).

[11] Executive Order No. 13953, 85 Fed. Reg. 62539 (September 30, 2020). https://www.govinfo.gov/content/pkg/FR-2020-10-05/pdf/2020-22064.pdf.

Table 2. 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, PGE's[12], 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[13]	**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

Alignment with DOE Strategy

DOE's three primary research and development (R&D) priorities related to critical minerals are: (1) Diversifying Supply, (2) Developing Substitutes, and (3) Recycling and Reuse. These R&D priorities aid in the development of resilient, sustainable, domestic CM supply chains to enable current and future clean energy and national security needs. Since 2014, the U.S. Department of Energy (DOE) Office of Fossil Energy and Carbon Management (FECM) and its national lab, 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. FECM's efforts have been closely coordinated with the Office of Energy Efficiency and Renewable Energy (EERE) and the Office of Science, which have both had longstanding programs in CM, especially EERE's Critical Materials Institute, an Energy Innovation Hub led by Ames Laboratory and managed by the Advanced Manufacturing Office. There has been a renewed push for collaboration across DOE on critical minerals through crosscutting teams—also including the Advanced Research Projects Agency–Energy (ARPA-E), Loans Program Office (LPO), National Nuclear Security Agency (NNSA), Office of International Affairs (IA), Office of Nuclear Energy (NE), and Office of Technology Transitions

Circular and Sustainable Supply Chains

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

Sustainability is an important aspect of the circular supply chain design. The two models do not exist fully independent of each other. Replacing the linear supply chain (in and out) model by using discarded materials aids indeveloping supply chains that meet the needs of the present without compromising the ability of future generations to meet their needs.

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

[12] Platinum group elements – platinum, palladium, rhodium, ruthenium, iridium, and osmium.

[13] See Environmental Protection Agency report for additional waste stream characterization. https://archive.epa.gov/epawaste/nonhaz/industrial/special/web/pdf/id-ch1.pdf.

(OTT)—and others to leverage each office's R&D and strengths to accelerate the development of robust domestic supply chains. More on this collaboration is provided in the final section of this document.

FECM's efforts have specifically focused on research, development, demonstration, and deployment (RDD&D) of the technologies necessary to advance CM production from unconventional and secondary sources, with many of these sources coming from coal-based waste materials from past mining.

These waste materials are in abundance and contain concentrations of valuable raw carbon ore[14] and CM. As such, the Division of Minerals Sustainability will prioritize the generation of high valued materials while reclaiming sites associated with legacy fossil fuel waste. The two commodity groups—CM and carbon ore-based products—are both extremely important to continued economic stability and national security. Deriving these materials from coal-based waste streams represents a tremendous opportunity to diversify CM supply, promote environment stewardship and expand future employment opportunities in the Nation's coal country. The production of CM or co-production of CM and carbon ore products from mining and processing waste increases materials in product circulation that can support the development of domestic circular supply chains and incentivizes cleanup of existing and abandoned mine sites. Deriving these commodities from coal-based waste streams provides an opportunity to remediate legacy fossil activities while creating employment opportunities in coal country. Mining and processing waste have the potential to be major contributors to a sustainable, critical mineral supply chain—which is needed for clean and renewable energy, battery storage technology, and electric vehicle (EV) production.

At the same time, the waste materials that house these critical minerals often have many other elements in low concentrations or trace amounts, some of which may be volatile and/or toxic. As novel processing technologies are developed or existing approaches are adapted to extract or produce CM or carbon ore, the Division of Minerals Sustainability will ensure that the safety of the workers and end users are always addressed with technologies that minimize and treat such waste material appropriately. Additionally, the life cycle of the critical minerals and carbon ore, including that remediated or reclaimed from waste or byproduct feedstocks will also be considered for technologies supported by the Division of Minerals Sustainability. As a part of FECM, special focus will be paid to approaches that can both produce critical minerals and reduce, capture, or remove carbon from the atmosphere, such as taking alkaline feedstocks in mine tailings and reacting them with CO_2 to sequester as carbonate or create composites to use as replacements for road or building materials.

Purpose and Scope

This Multi-Year Program Plan (Program Plan) presents the long-term vision, mission, and high-level goals of the Division of Minerals Sustainability within FECM. It is meant to catalyze industry establishment of circular domestic CM supply chains to bolster our transition to a clean energy economy. Technology development and the establishment of government- industry partnerships are essential throughout the entire supply chain, from upstream through downstream (i.e., from mine to product), for seamless integration of all aspects of CM and carbon ore production.

A DOE Request for Information (published in December 2020), a series of regional CM workshops, and a CM workshop with the National Laboratories were used to inform the development of this Program Plan. Success of program goals and timing will depend on future budget levels.

[14] Carbon ore defined here refers to only the fossilized and lithified (i.e., made into rock) plant matter or biomass component in coal. Coal commonly contains substantial quantities of mineral and rock fragment impurities that degrade the quality of the coal for refining purposes.

Vision and Mission Statements

VISION

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

- Clean energy deployment, including creating domestic manufacturing jobs;
- Secure, diverse, resilient, domestic critical minerals supply chains; and
- Environmental and social justice stewardship through co-production- and reclamation-based research and technology development.

MISSION

To support the U.S. transition to a carbon-free economy and a domestic clean energy manufacturing industry by leading the federal government's efforts to:

1. Characterize and assess domestic critical mineral and carbon ore resourses from fossil energy-related byproducts and related resources;
2. Develop advanced resource extraction, processing, and extractive metallurgical technologies; and
3. Evaluate the co-production potential of critical minerals and carbon ore for high-value products.

The Division of Minerals Sustainability's vision and mission are focused on producing unconventional and secondary feedstocks containing CM and carbon ore derived from previous and sustainable mining operations, as well as other fossil energy-related byproduct streams, such as produced water from natural gas and oil operations. This approach will augment recycling efforts, which are projected to relieve the pressure on primary CM supply but will not be sufficient to meet the demand required for EV and battery materials.[15]

Successful completion of this vision and mission will build upon previous successes and involve active engagement through a series of intra-agency (DOE), interagency [U.S. Department of the Interior (DOI), U.S. Department of Commerce (DOC), U.S. Department of Defense (DOD)], and 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 to launch and nurture domestic resource supply chains.

The productive uses of waste material for CM and advanced carbon products incentivizes cleanup of environmentally ravaged areas while producing the sustainable supply chains needed for clean energy in the near future. This strategy encourages job creation as the Nation transitions to clean energy, ensuring that the cost of the energy transition is not disproportionately borne by coal communities. The Division of Minerals Sustainability will develop advanced technologies to safeguard the

[15] International Energy Agency Report, The Role of Critical Minerals in Clean Energy Transition. https://iea.blob.core.windows.net/assets/24d5dfbb-a77a-4647-abcc-667867207f74/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf.

environment while supporting DOE's mission to ensure America's security and prosperity by addressing its energy and environmental challenges through transformative science and technology solutions.

This Program Plan was developed to encourage formation of government-industry partnerships to rebuild domestic CM 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.

Program Background

FECM's RDD&D program activities for CM production have demonstrated successful recovery of CMs from unconventional and secondary sources. Researchers have identified localities across the United States where coal by-products yield concentrations of rare earth elements[16] deemed to be economically producible. The Division has developed and validated several technologies for using coal-based and other unconventional and secondary sources as the basis for quickly increasing domestic CM production.[17] The RDD&D program has identified opportunities for creating new CM supply chains through upgrades to feedstock extraction,[18] concentration, extractive metallurgy, reduction, and alloying. This includes three 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.

Figure 3 illustrates pathways for the generation of CM and carbon ore products. After extraction, the material is separated into CM-rich and carbon ore-rich fractions for further processing. From co-production of CM and/or carbon ore from coal-based and other ore[19] materials, the Division of Minerals Sustainability is supporting the manufacturing of vital products needed for clean energy technology, while ensuring that the extraction and processing technologies are sustainable. Producing high-purity CM and/or high-value carbon products from unconventional and secondary sources also has the potential to advance low-income communities by (re)building a coal and mineral processing workforce and reclaiming the environment from adverse past practices involving mining waste products.

Circularity within the Department of Energy

A circular supply chain emphasizes 6 Rs: Recover, Reuse, Remanufacture, Recycle, Redesign, and Reduce.* One example of how such concepts are employed throughout DOE offices is:

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)

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

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

[18] Extraction defined here is the process of retrieving solid or aqueous mineral resources from the earth surface or subsurface.

[19] Ore – the naturally occurring material from which minerals or metals of economic value can be extracted at a reasonable profit. Source: American Geological Institute (AGI), 2011.

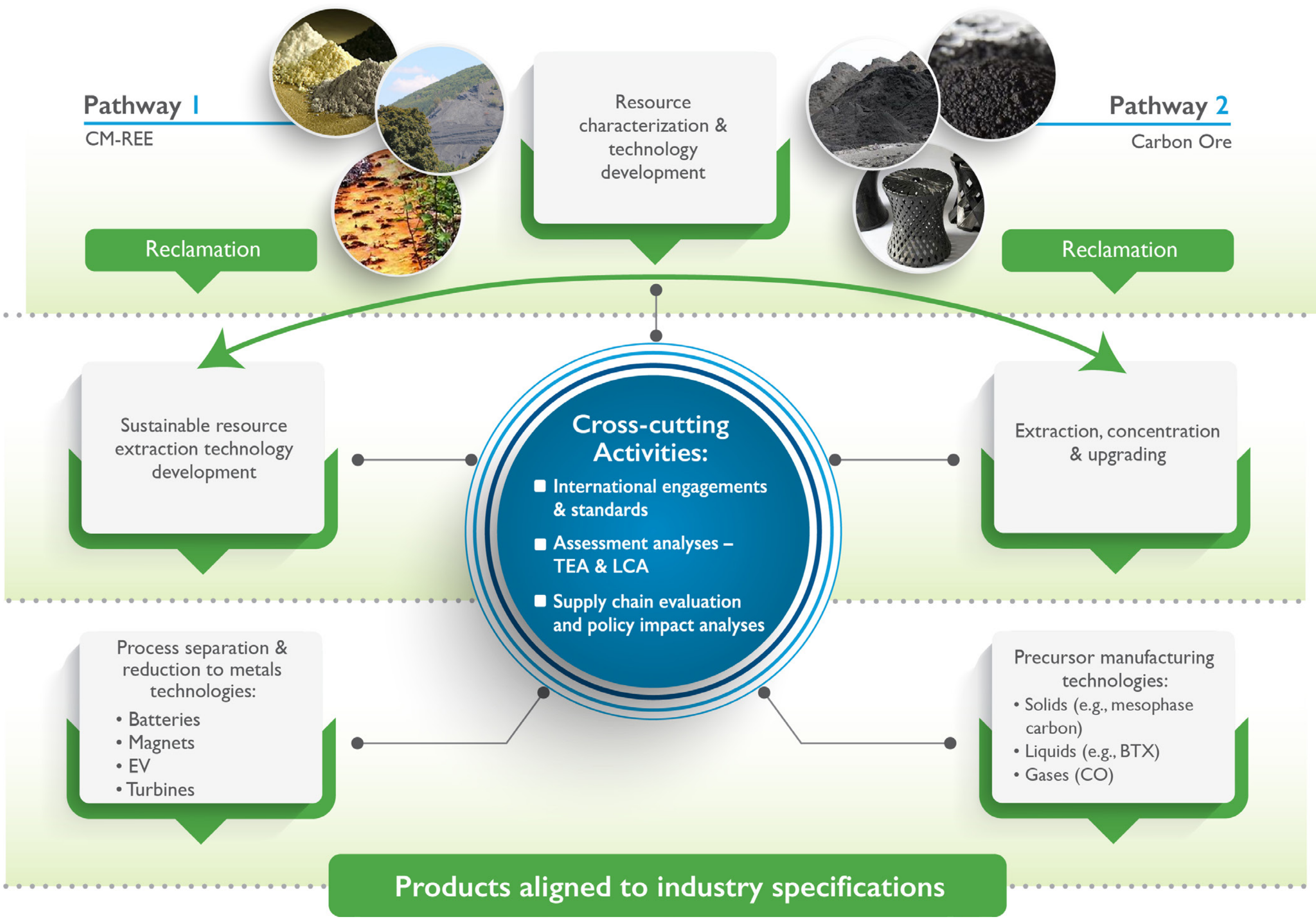


Figure 3. Coal-based Material Flow Chart for Co-production of CM and Carbon Products

The Division of Minerals Sustainability was founded to evaluate and address issues that enable creation of circular supply chain and sustainable practices. Resolving these issues requires innovative approaches that link upstream activities, midstream refining, and downstream customization to strengthen a domestic supply chain. The Division of Minerals Sustainability brings together manufacturers, not-for-profit entities, research organizations, and institutions of higher education to identify challenges, catalyze innovations, and develop cutting-edge rapid characterization methods, 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 manufacturing industries while making sustainability and safety core values.

Over the next several years FECM will focus its efforts on building and strengthening sustainable CM supply chains through unconventional and secondary sources that contain CM and carbon ore. These efforts will work synchronously with strategies to support the commercialization of high-value carbon ore products to advance domestic clean energy manufacturing. To achieve domestic, circular supply chains, it is important that, within the next five years, the new Division of Minerals Sustainability works to identify, access, and begin production of multiple unconventional and secondary sources.

Strategic Program Structure

The Program Plan as depicted in Figure 4 for the Division of Minerals Sustainability has three technical pillars:

Pillar 1 - ***Resource Characterization and Technology Development***: RDD&D 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 unconventional and secondary resources.

Pillar 2 - ***Sustainable Resource Extraction Technology Development:*** RDD&D will stimulate increased productivity for CM and carbon ore extraction and concentration from unconventional and secondary sources and promote environmental stewardship through maximizing productive use of materials and reduction of residuals.

Pillar 3a - ***Processing, Refining, and Alloying Technology Development***: RDD&D will advance environmentally-benign and economically efficient extractive metallurgy, separation, and reduction and alloying techniques and technologies for the production of high-purity CM, including rare earth metals. Technology development for recovered CM will advance the efficiency and environmental practices for processing, metal extraction, separation, and refining of CM from unconventional and secondary sources, expanding these products into new markets.

Pillar 3b - ***Processing and Manufacturing Technology Development:*** RDD&D efforts will focus 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.

Figure 4. Organizational Structure of the Division of Minerals Sustainability.

The three technical pillars are supported by crosscutting activities defined as:

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 CM and carbon ore standards (e.g., International Organization for Standardization) and trade policy that are essential to all three technology pillars. Development of international standards and partnerships are tools the United States can use to address the CM supply and high-value product manufacturing challenges that the Nation is now facing.

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 in August.

Source: International Organization for Standardization / US TAG ISO TC265

TECHNICAL PILLARS

To develop a circular CM supply chain, it is essential to address issues across the entire supply chain—from characterization and extraction to manufacturing, consumption, and finally recycling. Figure 5 illustrates an idealized mineral/metal supply chain that progresses from resource characterization and mining to the delivery of a refined product to clean energy manufacturing companies.

In developing this Program Plan, the Division of Minerals Sustainability focused its efforts on three technical pillars and a collection of crosscutting development efforts that benefit all three technology innovation areas. Figure 5 illustrates the interconnective nature of these four areas to fulfill the mission and vision of the Division of Minerals Sustainability.

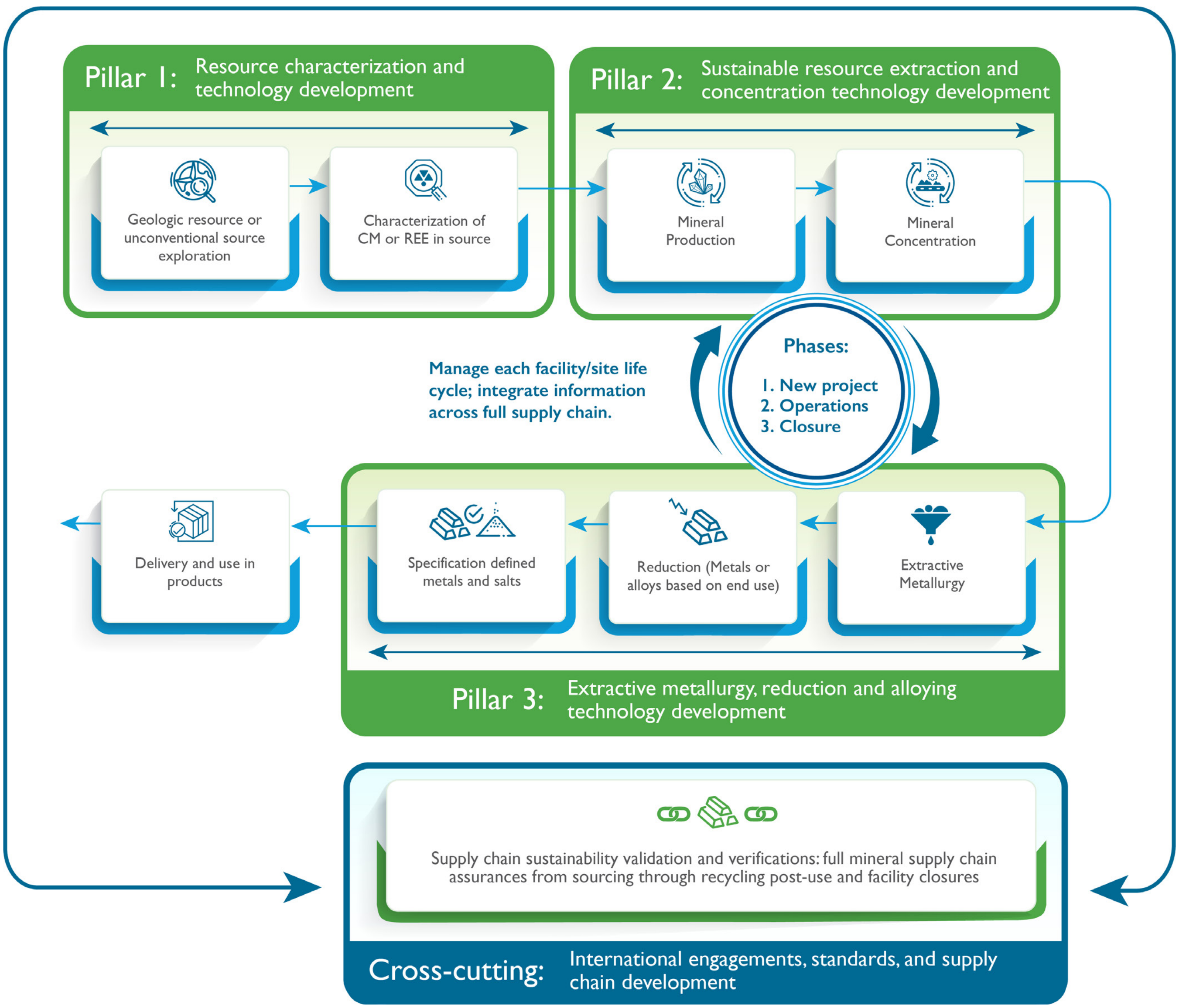


Figure 5. Structure of Critical Mineral Life Cycle Through the Various Stages of A Sustainable Supply Chain

Resource Characterization and Technology Development

RDD&D Direction

The U.S. reliance on CM imports can in part be addressed by increased investment in RDD&D for the U.S. mining, higher education system, and domestic industry. Mineral demand forecast scenarios consistent with climate goals project that the United States and global community are not capable of meeting lithium and cobalt (major EV battery materials) supply demands from existing mines and projects under construction.[20] The Division of Minerals Sustainability and its partners can leverage existing infrastructure and ongoing RDD&D to support the restoration of a sustainable domestic supply of CM.

Through many of these same partnerships, the United States can potentially advance its production of carbon products. 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 CM 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 CM 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 CM and carbon ore resource potential.
- *Resource Assessment 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 predict the location, concentration, and value of selected CM and carbon ore present in unconventional and secondary sources.

Success in this RDD&D area will depend on strong collaborative partnerships with other federal and state government agencies (e.g., USGS).

[20] International Energy Agency Report, The Role of Critical Minerals in Clean Energy Transition. https://iea.blob.core.windows.net/assets/24d5dfbb-a77a-4647-abcc-667867207f74/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf.

RDD&D Requirements

To address the expansion of the list of potential CM sources and the associated carbon ore, as well as to reduce costs for resource characterization and recovery (Pillar 1 in Figure 5), the following pathways have been identified:

- **Characterization for 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 CM 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 CMs. 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 CM and associated carbon ore resource prediction and assessment.
  - Integration of multiple technologies such as geophysical (i.e., seismic, magnetic, and gravity) surveys, LiDAR and ariel imagery, and digital bore hole and core scanning 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 CM and carbon ore occurrence probability models with calculated uncertainty. Using AI/ML, sample and field characterization results can be seamlessly integrated into regional resources models for calculating resources in unconventional and secondary sources.
  - Regional and national AI/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 CM and/or carbon ore in unconventional and secondary feedstocks.

Novel Data-Driven Assessment Tool

To meet the projected demand for the clean energy transition, NETL has developed a methodology (NETL URC assessment method) and tools to systematically predict and assess REE resources from coal deposits and other sedimentary systems. Utilizing data analytics and machine learning capability, this technique identifies and predicts anomalous concentrations of CM in coal deposits. Intra/inter-governmental, academic, and industry collaborations have been vital to fill in the detailed, finer-scale data needed to improve, test, and validate the unconventional REE/CM assessment approach.

Performance Metrics for RDD&D

Key Milestones and Deliverables:

- Identify and validate 'most appropriate' novel field and laboratory technologies and techniques with high accuracy and precision.
- Develop standardized protocol and best practices for field and laboratory characterization methodologies.
- Develop standardized occurrence probability models that utilized newly collected and historical sample and field characterization results.
- Develop regional and national (AI/ML-based) approaches that predict the location and estimated resource concentration and value of unconventional and secondary sources.

Sustainable Resource Extraction Technology Development

RDD&D Direction

CM supply chain optimization and the development of high-quality carbon products require rigorous application of the latest extraction and concentration technologies to maximize resource recovery while demonstrating reduced risk and improved environmental and economic performance. Crucial steps for sustainable extraction and concentration technologies include:

- **Transformational, Unconventional, and Conventional Extraction Technologies**: Research aims to develop novel strategies and technologies to safely extract CM and carbon ore from unconventional and secondary sources in an environmentally benign manner.
- **Integration of Industrial Beneficiation Methods and Technologies**: Developing innovative technologies and concentration strategies for processing CMs and carbon ore. Technologies could increase CM concentration by a factor of 5-10 and increase the quality of carbon ore through beneficiation.
- **Remediation of Existing Sites and Abandoned Mine Residuals**: Production of CM 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.

RDD&D Requirements

In order to produce high-purity CM and carbon ore from unconventional and secondary sources, new technologies and strategic partnerships will be required to improve extraction and concentration in a sustainable manner through the following pathways:

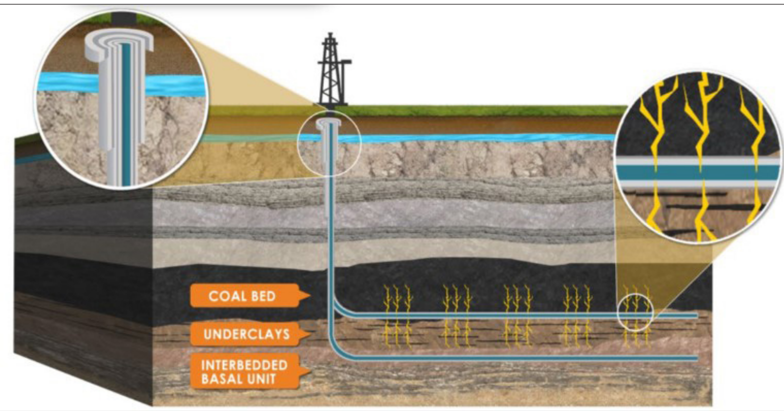


Illustration depicting in-situ recovery process from undisturbed sedimentary rock layers, open pits, or underground mines using novel organic leaching acid to extract and recover REE (Verba, 2021, NETL)

- **Transformational, Unconventional, and Conventional Extraction Technologies.** Research within this area will build off existing and new technologies that improve efficiency and yield while minimizing waste and risk. Development and field validation of technologies and techniques include:
  - Targeted "selective" horizonal drilling, in-situ leaching, agromining,[21] or biomining to extract only the desired material from the host rock.
  - Database of microbial-mineral interactions and data-driven (i.e., AI/ML) analysis techniques reduce uncertainty in the application of appropriate biomining reagent(s).
  - Novel filters and membranes technologies for improved CM recovery for high-specificity separations from wastewaters.

Improved Extraction Processes

The Minerals Sustainability Division has supported RDD&D projects that develop extraction technologies to increase the concentration of CM- and carbon ore-bearing materials. Researchers have developed an environmentally benign and efficient processing technology that is capable of extracting and concentrating REE in-situ from shales and clay-rich waste materials. Advancing a commonly practiced industry method, researchers developed a novel leaching liquid that does not employ acids to extract and concentrate REE from fine coal waste materials. The project successfully produced a solution containing a final REE concentrate of 15-18% REE by weight.

[21] Agromining involves growing selected hyperaccumulator plant species (plants that accumulate very high concentrations of certain metals) on low-grade ore bodies, mineralized soils, or anthropogenic metal-rich materials (e.g., contaminated soils, mine spoils, industrial sludge), followed by harvesting and incineration of the biomass to produce a 'bio-ore' from which target metals or salts may be recovered. Source – Nkrumach, P.N. et al., 2021, Agronomy of 'metal crops' used in Agromining, in van der Ent, et al., eds., Agromining: Farming for Metals, pp. 23-46.

- **Integration of Industrial Beneficaition Methods and Technologies**. Production of highly enriched CM or carbon ore concentrate 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 CM 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 CM 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. 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.

Performance Metrics for RDD&D

Key Milestones and Deliverables:

- Develop and validate extraction techniques and technologies to safely extract CM and carbon ore from unconventional and secondary feedstocks.
- Develop and validate extraction techniques and technologies (e.g., filters and membrane distillation) for unconventional and secondary wastewater feedstocks.
- Develop and test technologies for onsite concentration and demonstrate: (1) an increase in CM concentration from unconventional and secondary sources, (2) an economical method for recovery of fine-grained coal particles that would be lost to impoundment, and (3) an increase in high value materials from coal wastes through concentration.
- Design of best practices to categorize and prioritize mine sites considering factors such as risk assessment and resource concentration.

Processing, Refining, and Alloying Technology Development

RDD&D Direction

U.S. mineral processing and smelting facilities are not adequate to meet the demands for clean energy technology manufacturing. Many of these functions have been offshored. In 2016, several domestic metal mines and mineral processing facilities were idled or closed permanently.[22] The intent of this pillar is to support research initiatives that lead to environmentally benign, efficient, and cost-effective technologies for the separation, processing, and/or reduction to metals of CM 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 in this space are only a fraction of the overall RDD&D, it is of special importance to engage with EERE and other offices within DOE and DOD to coordinate RDD&D efforts, share information on novel processing technologies, and create synergies that will accelerate the development of domestic supply chains. RDD&D efforts will be focused on the three key areas outlined below:

- **Advanced Individual Separation and Reduction to Metals**: Research will not only address current conventional technologies used to produce individual REE and/or CM from high-purity mixed concentrates with subsequent conversion to metals for alloying, but also advanced or new novel individual separation and reduction to metals processes that have potential for 20% lower capital and operational expenditure costs than current conventional standard practice.
- **Enable Commercial Production**: Research will identify innovative pathways (spanning processing and separation) to improve productivity, reduce costs, and lessen environmental impacts. This includes developing concepts to improve the purity and quantity of affordably produced CM and REE.
- **First-mover and Second-generation Large-scale Pilot Projects**: Research will enhance production of CM from unconventional and secondary sources in larger pilot-scale circuits.[23] New transformational facilities will build upon previous generations to improve environmental performance and reduce operational costs.

Demonstrated Feasibility of Producing High Quality REE

Since 2014, bench-scale research and first-of-its-kind small-scale pilot facilities have demonstrated the technical feasibility of producing small quantities of high-purity MREO and/or Mixed Rare Earth Salts (MRES). Recent achievements include the design, construction, and operation of three 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.

[22] This list includes iron ore mines in Michigan and Minnesota; three primary aluminum smelters in Indiana, Missouri, and Washington; one secondary zinc smelter in North Carolina; a titanium sponge facility in Utah, the only such facility in the U.S.; and titanium mineral operations in Virginia.

[23] Circuits are individual links or stages (e.g., grinding, flotation, elemental separation) within the entire mineral processing procedure. A mineral processing facility will consist of several linked circuits that will be optimized to improve productivity and efficiency.

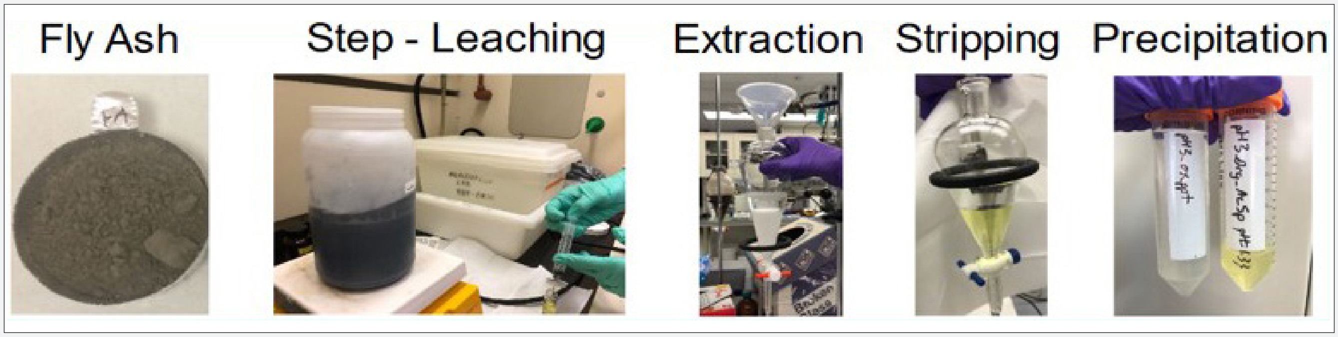
The development and validation of innovative technologies for processing will maximize the production potential of CM to decrease risk of projects to market volatility. Design strategies for process integration and processing facilities that can minimize processing steps and chemicals needed for metal extraction and separation will decrease capital and operational expenditures.

RDD&D Requirements

The clean energy transition will require the United States to secure an uninterruptable supply of the minerals and materials needed for clean energy technologies. RDD&D being conducted will help enable industry to establish secure supply chains for CM. Specifically, FECM is providing the research pathways for commercial production of CM and REE metals in the following three key areas:

- **Advanced Individual Separation and Metallization:** The goal of this research is to improve the overall recovery and purity of CM and individually separated, high-purity (ISHP) Rare Earth Oxides (REO) and/or Rare Earth Salts (RES). RDD&D is developing advanced, environmentally benign, reduced cost, ISHP and reduction to metal concepts. RDD&D efforts will be performed in conjunction with intermediate and/or end-product supply chain manufacturers, thus bracketing production and supply of REE and CM from unconventional and secondary sources to commercial or defense product production.
- **Enable Commercial Production**. Innovative new 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 for innovative pathways to current approaches. Results from testing will be used to prepare techno-economic assessments comparing existing processing systems with innovative technology substitutes.
    - Identify and increase domestic REE, CM, and carbon product co-production potential to make metal extraction, separation, and recovery processing more economical and profitable. Development of thermodynamic and kinetic databases with AI/ML capabilities will reduce uncertainty in the application of appropriate metal extraction and separation techniques for specific unconventional and secondary sources.
- **First Mover and Second-generation Large-scale Pilot Projects**. Research activities in this area focus on the initiation and eventual scale up to larger-scale pilot projects from the first-generation, capable of producing 1-3 metric tons/day MREO and MRES, to second-generation demonstration/near commercial projects that can produce 10 metric tons/day MREO and MRES. Both facilities will have the capability to perform individual, high-purity separations and reduction to metals.

Advances within this research pillar will be focused on environmentally-friendly technologies that provide pathways to minimizing disturbance of ore-bearing lands and maximizing environmental stewardship.



Novel REE Recovery process for Powder River Basin Ashes to Reduce Extraction Steps and Conditions (Lopana, 2021 NETL)

The Carbon Ore, Rare Earth, and Critical Mineral (CORE-CM) Initiative

Emphasizing unconventional and secondary sources, regional assessments are an essential link between the resource characteristics within a region and opportunities to develop robust circular supply chains. Transportation costs may impact the carbon footprint of any commodity. The Carbon Ore, Rare Earth, and Critical Minerals (CORE-CM) Initiative for U.S. Basins is a further step toward achieving the goal of comprehensive resource assessment technologies and local development of supply chain elements near the raw resources.

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.

To promote environmental justice and reduce the occupational health and safety impacts associated with any proposed products, CORE-CM Initiatives and the Division of Minerals Sustainability will identify environmental, health, and safety requirements pertaining to:

- Processing (extraction, concentration, metal extraction, and separation) of raw materials.
- Shipping, receiving, storage, handling, and use of raw materials to manufacture products.
- Field modifications and installation (e.g., cutting, drilling, finishing) of manufactured products.
- Long-term use of the manufactured product in residential, commercial, and industrial settings.
- Demolition, removal, and recycling of end-product for reintroduction to supply chain.

Performance Metrics for RDD&D

Key Milestones and Deliverables:

- Develop novel environmentally benign processes for the extraction, separation, and recovery of CM and REE that minimize consumption of chemicals and production of waste materials.
- Development of processing capabilities for the economic production of additional CM from unconventional domestic feedstock resources for use in clean energy manufacturing.
- Initiate final design, construction, and operation of first-generation facilities that can produce 1-3 metric tons/day MREO and MRES as well as co-produce CM and other primary products (e.g., zeolites and ash for cement industry).
- Initiate, design, construct, and operate facilities to produce individually separated, high-purity, REE and CM as well as facilities for reduction of individual or binary MREO metals that meet end-user required specifications.
- Design, construct, and ultimately deploy second generation demonstration/near commercial MREO facilities that produce 10 metric tons/day MREO and MRES and have capabilities for producing individually separated, high-purity REO/RES and subsequently reduction to metals.

Processing and Manufacturing Technology Development

RDD&D Direction

Coal has been a critical domestic resource, contributing to U.S. economic growth for over a 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. Efforts by the Division of Minerals Sustainability in this area focus on three key areas, as outlined below:

- **Building and Infrastructure Development**: Research in this area seeks to support the development of high-value building and infrastructure materials from carbon ore through development of large-scale, alternative use pilot projects. First generation pilot projects identify and develop technologies to transition from batch to continuous production of carbon ore-based materials. Advancing these transformational technologies will enable domestic production of strategic materials and superior building products from carbon ore—materials and products that have minimal emissions, superior product performance, and better lifecycle characteristics for new and existing products in the market.

- **Advanced Carbon Material Production**: Research activities within this area include the development and scale-up of lab/bench-scale, efficient processing technology to produce marketable, carbon ore tar-derived, mesophase precursor pitch to produce highly specified carbon products (e.g., carbon fiber, graphene, graphite).
- **Reinvest in Critical Supply Chains**: Research in this area includes developing strategies to establish resilient supply chains that enable products such as graphite and silicon production from domestic coal and coal byproducts. Advancing this research is critical to domestic production of silicon metal used in solar photovoltaic and semi-conductors, and development of synthetic graphite for lithium-ion batteries.

RDD&D Requirements

In order to advance carbon ore-derived carbon products, the Division of Minerals Sustainability has developed a roadmap that includes the following recommended key areas:

- **Building and Infrastructure Development**. Research activities in this area focus on the initiation and eventual scaling up of large-scale pilot projects from batch production to continuous production of carbon-ore derived building and infrastructure materials. This research area will include the following:
  - Design, construct, and operate production systems producing carbon ore derived roofing tiles and other building materials, carbon foam for building materials and aerospace applications.
  - Structural components for transportation such as roads, tunnels, and bridges; functional materials for wastewater treatment and solid-waste management; and seawalls and levees.
  - Transformational building technologies of the future, including siding, decking, insulation, joists/studs, sheathing, tiles, carpet, wraps and veneers, and architectural blocks that have superior strength and insulation.
- **Advanced Carbon Material Production**. Research will develop and test concepts at lab/bench-scale for innovative pathways to produce carbon ore-derived, mesophase pitch precursors for production of carbon products.
  - Convert carbon into feedstocks for clean energy manufacturing via cleaning, distillation, and other processes, and identify new market opportunities for carbon ore-derived, mesophase pitch.
  - Carbon-derived graphite for anodes and other applications.

Potential New Carbon Ore Markets

Current research conducted by DOE-FECM and NETL is examining new applications and new markets for carbon ore. The Division has supported two projects to develop anodes for Li-ion batteries. Graphite has been the key component for Li-ion battery anodes. Projected market demand growth is anywhere between 6- to 30-fold increase by 2040.* Research has shown potential in using synthetic graphite from carbon ore in production of a polymer-derived ceramic to produce commercially viable anodes that can rival the performance of graphite in Li-ion batteries. Additional R&D is developing an economically viable process of converting carbon ore to anode-grade graphite.

(*) International Energy Agency Report (2021)

  - Large-scale production of graphene, nanotubes, carbon fibers, and other high-value carbon products.
  - Scale-up efforts will be accomplished through the transition of batch to continuous production of carbon ore derived mesophase pitch. Validated concepts and improvements can be scaled up to large-scale pilot facilities for production of highly specified carbon products.

- **Reinvest in Critical Supply Chains**: Research activities focus on improving the supply of critical materials derived from carbon ore for products required in the semiconductor and solar photovoltaics supply chains. This includes developing novel technologies that improve the energy efficiency of common practices (i.e., graphitization and calcining) and/or identifying carbon ore-based substitute additives that meet source specifications for the manufacturing industry. Successful projects will advance to higher Technical Readiness Levels (TRL) to produce high-purity silicon and graphite from carbon.

Performance Metrics for RDD&D

Key Milestones and Deliverables:

- 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.

IMPLEMENTATION PLAN

The Office of Fossil Energy and Carbon Management has considerable experience working with other DOE offices, state and federal agencies, academic institutions, industry, and non-governmental organizations to research, develop, demonstrate, and deploy new technologies in areas such as carbon capture and storage, reduced emissions technologies for power plants, and unconventional resource development. For the past seven years, FECM has deployed that expertise to help enable the development of robust, secure, environmentally sustainable domestic supply chains for critical minerals and carbon ore from unconventional and secondary sources within the next decade.

Budget and Program Goals

Prior budgets (Figure 6) have set a foundation for the Division of Minerals Sustainability to gain a firm understanding of the landscape of technology needs for identifying potential critical mineral and carbon ore resources, extraction and concentration techniques, extractive metallurgy technology, and precursor manufacturing processes associated with coal, coal byproducts, and coal refuse.

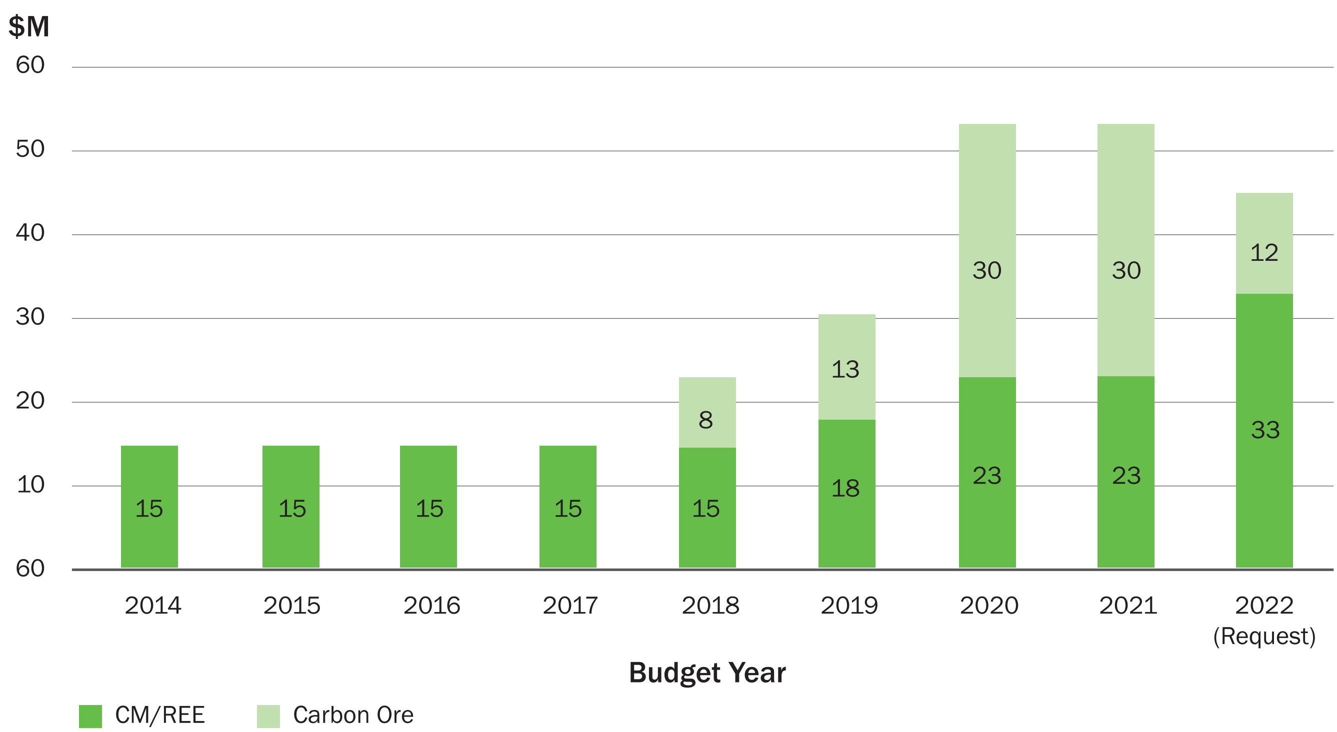


Figure 6. Historical FECM Budgets in Rare Earth Elements, Critical Minerals, and Carbon Ore R&D

This knowledge has enabled the generation of the RDD&D requirements, goals, and milestones (Table 3) needed to accelerate the development of sustainable CM supply chains and advance production of high-value carbon products by 2030.

Table 3. Division of Minerals Sustainability Program Goals

Division of Minerals Sustainability Specific Mission Sub-Areas	Program Goals by Topical Area (2021-2030 Range)
Resource Characterization & Technology Development • Characterization and opportunities – resource potential from unconventional and secondary sources. • Core/sample, outcrop, and regional characterization – technologies, techniques, and geospatial database • Resource assessment and predictive capabilities – dynamics imulations.	**Critical Minerals** *Within 5-7 years*, demonstrate predictability of quantifiable domestic unconventional and secondary CM resources (including sufficient quantities of Rare Earth Elements) to support projected industry demand growth of at least 5% per year through 2028. **Carbon Ore** *Within 3 years*, develop verifiable estimate of CM and carbon ore from unconventional and secondary sources known to have CM and evaluate carbon ore recovery potential and products.
Sustainable Extraction Technologies • Transformational, conventional, and unconventional extraction technologies. • Integration of concentration methods and technologies into industrial processes, as appropriate, for improved environmental process performance and energy efficiency. • Remediation of existing and legacy mine residuals for the reduction and elimination of mine residuals and waste materials.	**Critical Minerals** *Within 5-7 years*, demonstrate and validate reduced risk, environmentally sustainable and economic next generation extraction and concentration strategies and technologies. **Carbon Ore** *Within 3-5 years*, demonstrate cost effective recovery of high-value carbon ore from CORE-CM identified sources.
Processing, Refining, and Alloying Technologies (CM) • Advanced individual separation and reduction to metals technology development and validation. • Enable commercial production—identify innovative pathways (processing and separation) to improve productivity and environmental performance while reducing costs. • Demonstrate capability to produce CM from unconventional and secondary resources and optimize modular processing circuits for sustainable and cost-effective production. • Enabling utilization of carbon ore for high-value products.	*Within 3-5 years*, demonstrate first generation capability to produce 1-3 t/day of MREO or MRES and other CM. *Within 5-7 years*, develop and make operational four pilot-scale units with sufficient production capability of MREO/MRES and other CM to meet projected demand growth of at least 5% per year of refined product for the 5-year period from 2024 through 2028. *Within 10 years*, enable construction of commercial-scale facilities capable of producing 1,000 t/year MREO. Facilities will focus on unique and technically recoverable sources. Replication of proven designs would allow production to scale up to 10,000 tons MREO annually.
Processing and Manufacturing Technologies (Carbon Ore) • Building and infrastructure development. • Advance carbon material production. • Reinvest in critical supply chains.	*Within 3-5 years*, demonstrate cost-effective substitution of carbon from coal waste to produce synthetic graphite and create precursor materials for carbon fiber and graphene. *Within 10 years*, demonstrate uninterruptable supply of high-purity silicon metal (polysilicon) derived from carbon ore products.
Cross-cutting activities: International engagement, standards, and supply chain development • Development of consistent international standards for sustainable CM supply chains. • Nurture beneficial international engagements. • Validate and verify progress toward sustainable CM and REE supply chains. • Develop policy and systems analyses. • Develop Life Cycle Analysis (LCA) and Environment, Safety and Health (ES&H) standards for all products produced from carbon ore.	**Critical Minerals** *Throughout next 10 Years*, develop and participate in international policy and market engagements aimed at ensuring an uninterrupted domestic supply of CM and end products. **Carbon Ore** *Within 5 years,* participate in international standards organizations and support market engagements to make coal waste sources acceptable feedstocks for premium carbon products.

Engagement Outside FECM and DOE

For more than a decade, DOE has been a leader in addressing critical supply chain challenges, with demand increasing in scope and magnitude. The Division of Minerals Sustainability is one of several DOE Offices and Divisions that are addressing CM/REE development and deployment. This Division of Minerals Sustainability is committed to collaborating with the other DOE Offices—ARPA-E, EERE, IA, LPO, NE, NNSA, OTT, and SC—as part of crosscutting efforts to support DOE's five technical priorities: (1) Diversifying Supply, (2) Developing Substitutes, (3) Recycling and Reuse, (4) Systems Analysis, and (5) Demonstrations (Figure 7).

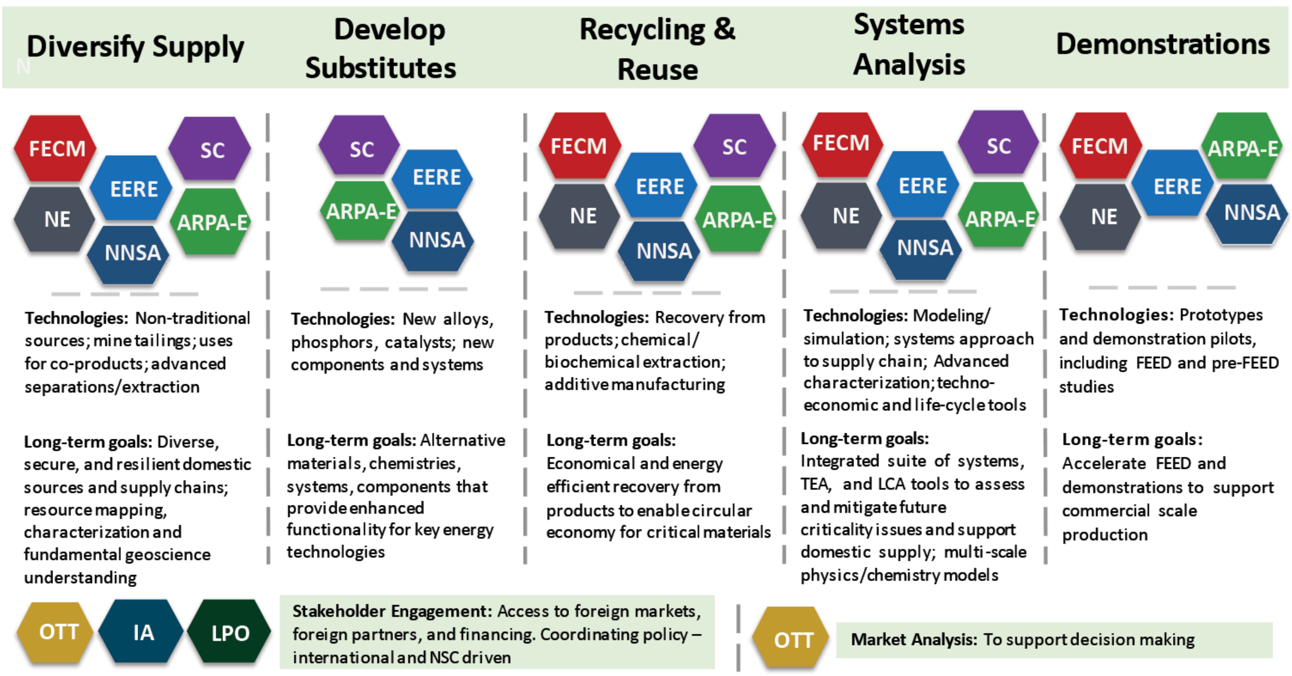


Figure 7. Department of Energy's crosscutting engagements to address materials supply risks, prevent supply chain disruptions, and advance production of critical minerals and high-value carbon products

In particular, the Division of Minerals Sustainability collaborates closely with EERE to support applied research, development, and demonstration (RD&D) across most topics, while SC provides the necessary fundamental research and world-class user facilities necessary to complete much of the related work, and ARPA-E targets the development of specific technological advances. The Division also collaborates closely with IA, LPO, and the OTT to effectively engage with stakeholders, both foreign and domestic. Additionally, the Division of Minerals Sustainability will take advantage of the knowledge and expertise inherent across the entire National Laboratory complex to inform and complete its RD&D.

Other Governmental and Non-Governmental Partnerships: DOE plays a leadership role in the Federal Government's efforts in the area of CM, including: (1) 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 CM; and (2) the U.S. House Committee on Homeland and National Security that oversees the Critical Mineral Subcommittee. As such, the Division of Minerals Sustainability works with DOE colleagues to contribute to both of these subcommittees.

Additionally, the Division of Minerals Sustainability seeks to identify strategic opportunities to collaborate with external agencies outside of the NSTC. In particular, the Division of Minerals Sustainability will seek robust collaborations with the DOI/USGS and the EPA on issues related to assessing, extracting, and concentrating critical minerals from unconventional and secondary sources, and seeks to aid the DOD, DOC, DOS, and DHS by providing technical and other support for the generation of resilient, domestic supply chains for critical minerals and high value carbon products. Furthermore, the Division of Minerals Sustainability will continue to engage with other federal, industry, and international organizations, such as the National Institute for Standards and Technology (NIST), EPA, and USGS, on the development of sustainable standards for critical minerals and rare earth elements.

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 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 the 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.

Program Performance Assessments

The Division of Minerals Sustainability employs several program-management processes to ensure the effective use of taxpayer funds, including:

- Developing targets and milestones for all RDD&D pathways in close consultation with experts in industry, end users and customers, and the scientific research community.
- A rigorous competitive-selection process to ensure projects are selected based on technical feasibility, high-impact potential, innovation, and the likelihood of making progress toward DOE's milestones and targets.
- External review and evaluation processes, which include program reviews by outside experts, such as the National Academies.

U.S. DEPARTMENT OF ENERGY

Fossil Energy and Carbon Management