The U.S. Department of Energy's Critical Minerals and Materials Program:

Building Secure Supply Chains for America's Energy Future

U.S. Department of ENERGY™

WHAT ARE CRITICAL MINERALS AND MATERIALS (CMM)?

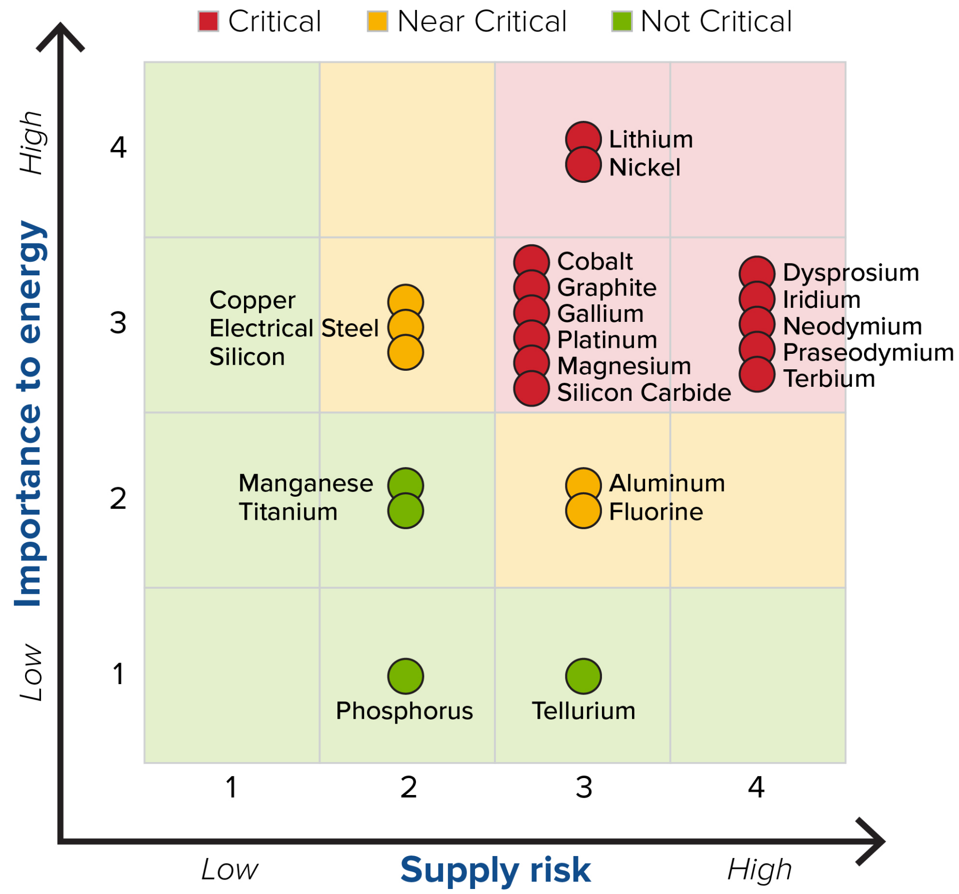
A critical *material* is:

Any non-fuel mineral, element, substance, or material that the Secretary of Energy determines:

- Has a high risk of supply chain disruptions.
- Serves an essential function in one or more energy technologies, including technologies that produce, transmit, store, and conserve energy.

One of 50 commodities designated as critical *minerals* by the Secretary of the Interior.

MEDIUM TERM 2025-2035



Medium Term Criticality Matrix from *Critical Materials Assessment* (DOE 2023). DOE has determined the eighteen materials in yellow and red to be critical materials for energy (the "Electric Eighteen").

THE “ELECTRIC EIGHTEEN” CRITICAL MATERIALS

Critical Materials are Vital to the Energy Sector, National Security, and U.S. Competitiveness

Neodymium, Praseodymium, Dysprosium, and Terbium	**Magnets** for wind turbine generators and EV motors
Cobalt, Lithium, Graphite, Nickel, and Fluorine	**Batteries** for electric vehicles and grid storage
Iridium and Platinum	**Electrolyzers** for green hydrogen production and **fuel cells** for energy storage
Gallium and Silicon Carbide*	**Semiconductors** that enable high voltage power and efficient lighting
Magnesium and Aluminum	**Lightweight alloys** for transportation
Silicon*	**Solar panels**, lightweight alloys, electrical steel
Copper* and Electrical Steel*	Wind turbine **generators** and EV **motors**

Goals

- **100% clean electricity by 2035**
- **Net-zero economy by 2050**
- **50% EV adoption by 2030**
- **30 GW offshore wind by 2030**
- **Cost of Clean Hydrogen $1/kg by 2031**

**Not on the U.S. Geological Survey Critical Minerals List*

THE CHANGING CMM LANDSCAPE

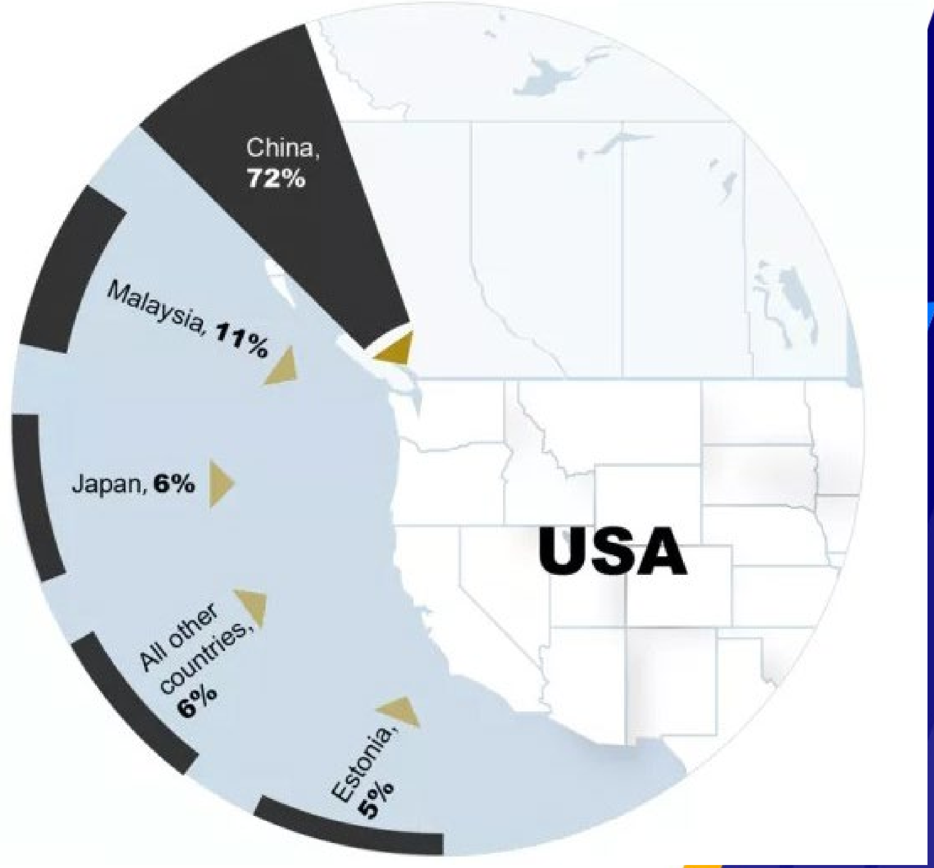
CMM are **vital ingredients** in not only clean energy technologies,
sensors, consumer electronics, and other end uses.

CMM **demand growth is accelerating** as countries work to reduc
deployment.

Limited domestic CMM supplies and capabilities in the United
particularly in midstream processing and refining, pose economic a

Some **vulnerabilities** are material-specific, while others apply to C

The **Bipartisan Infrastructure Law (BIL)** and **Inflation Reductio**
DOE’s CMM work.



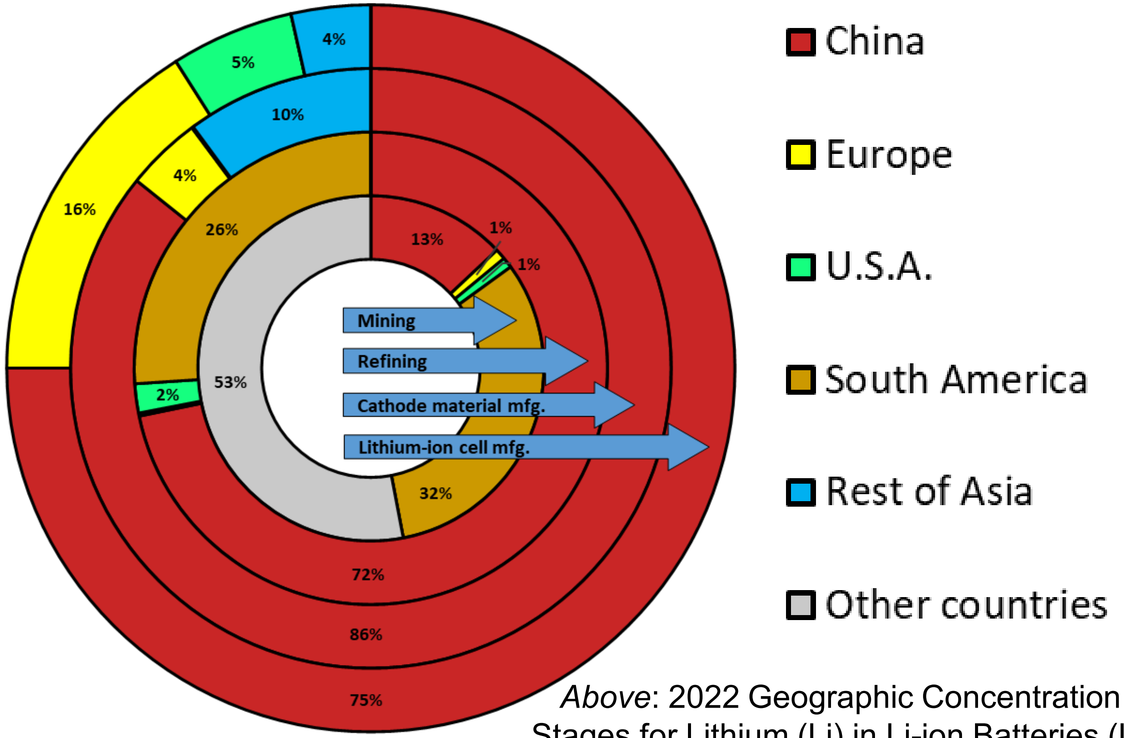
Sources of U.S. Imports of Rare Earth Compounds and Metals, 2019-2022. (GAO 2024 analysis of USGS data.)

DOE is dedicated to strengthening and securing CMM supply chains for America's energy future.

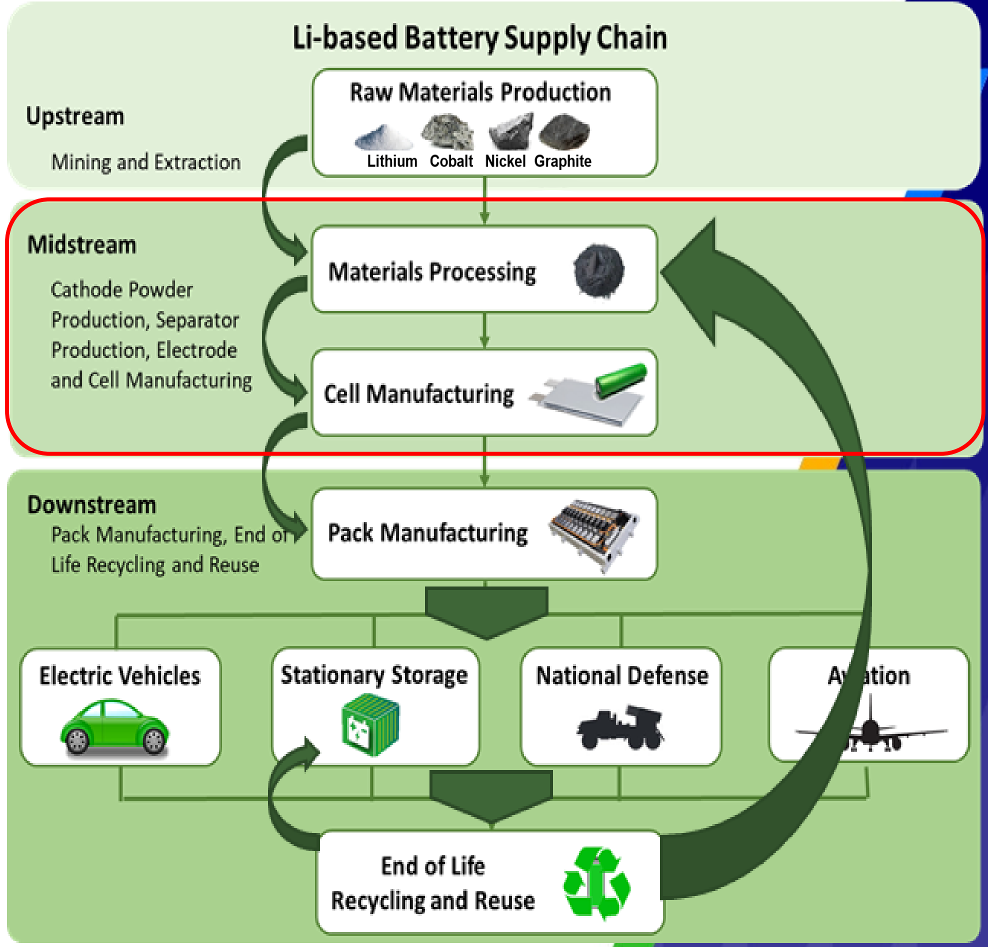
CMM SUPPLY CHAIN VULNERABILITIES

Upstream to midstream capabilities are geographically concentrated for many CMM (e.g., lithium).

Lack of midstream capabilities limits growth of upstream supply and downstream value-add manufacturing, even in cases where domestic raw materials are abundant.



Above: 2022 Geographic Concentration of Supply Chain Stages for Lithium (Li) in Li-ion Batteries (LIB) (Source: Data compiled by DOE AMMTO.) *Right*: Li-based Battery Supply Chain (Source: "Review of Large Capacity Batteries," DOE chapter in *100-Day Reviews under EO 14017* (The White House 2021.))



FOREIGN DEPENDENCE IN 2023

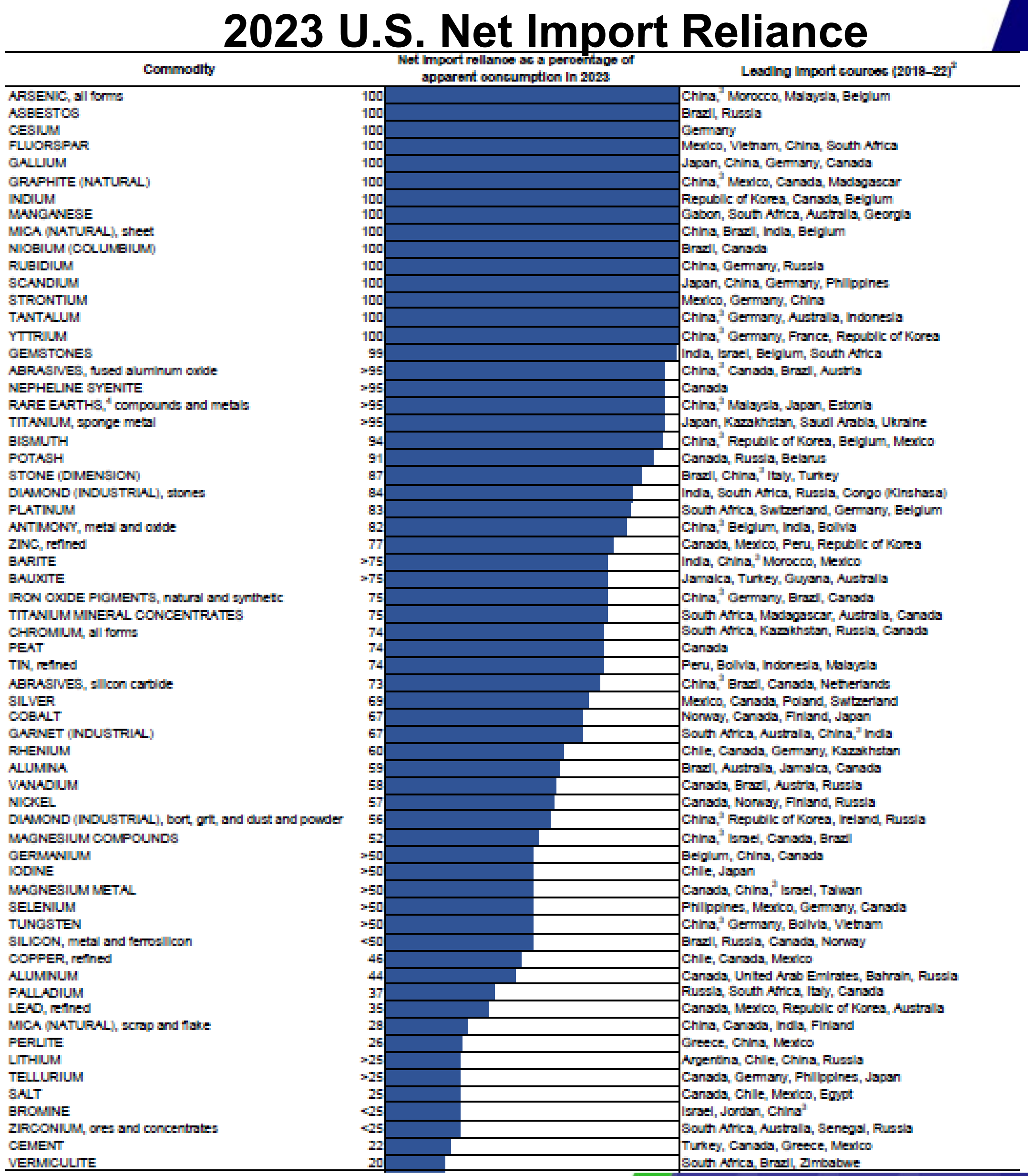
In 2023, the United States was:

- 100% net import reliant for 12 of the 50 critical minerals.
- More than 50% net import reliant for an additional 29 critical minerals.

China was the leading producer for 29 of the 43 critical minerals for which information was available to make reliable estimates.

Australia and South Africa are leading producing nations of three critical minerals each and the Democratic Republic of the Congo is the leading producer of two critical minerals.

[Mineral Commodity Summaries 2024, USGS]



2023 U.S. Net Import Reliance

Commodity	Net import reliance as a percentage of apparent consumption in 2023	Leading import sources (2018–22)[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

ADDITIONAL VULNERABILITIES AND CHALLENGES

- Material processing equipment challenges (foreign sourcing and long lead times)
- Capital availability
  - Mineral price volatility, high startup costs, long permitting timelines, and the current interest rate environment are keeping private capital on the sidelines.
- Price and inventory volatility
  - Price manipulation by China hurts the economics of domestic mineral projects (Jervois Cobalt in ID).
  - Rapidly changing market for different battery chemistries creates unclear demand roadmap.
- Geopolitical instability and resource nationalism
  - Globally, export restrictions on critical raw materials increased five-fold over the last decade.
  - China raised the number of restrictions on critical raw materials needed for EVs—including lithium, cobalt, and manganese—nine times from 2009 to 2020.
- Market volatility caused by duties and tariffs
- Shortage of trained and skilled workers in CMM space
- Environmental and human impacts of production.
  - Without innovation, onshoring parts of CMM supply chains will remain economically unviable; with high water, chemical, and energy intensities, they struggle to meet U.S. environmental and human health standards.

DOE'S ROLE IN THE FEDERAL LANDSCAPE

- **DOE's primary role is to advance research, development, demonstration, and commercial deployment spanning basic science to technology innovation.**
  - Supported by analyses, domestic and international standards, and international collaboration with allied countries.
- DOE does not have regulatory authority to issue permits for critical minerals or materials activities.
- DOE partners with other federal agencies on publications and initiatives:
  - Critical Materials Collaborative (CMC)
  - Federal Strategy on Critical Minerals
  - Mining Reform
  - National Blueprint for Lithium Batteries
  - American Battery Materials Initiative
  - International Conference on Critical Minerals and Materials
  - Minerals Security Partnership (MSP)

DOE is an integral part of an All-of-Government Strategy | www.criticalminerals.gov

INVESTMENT AND INNOVATION FOR SECURE CMM SUPPLY CHAINS

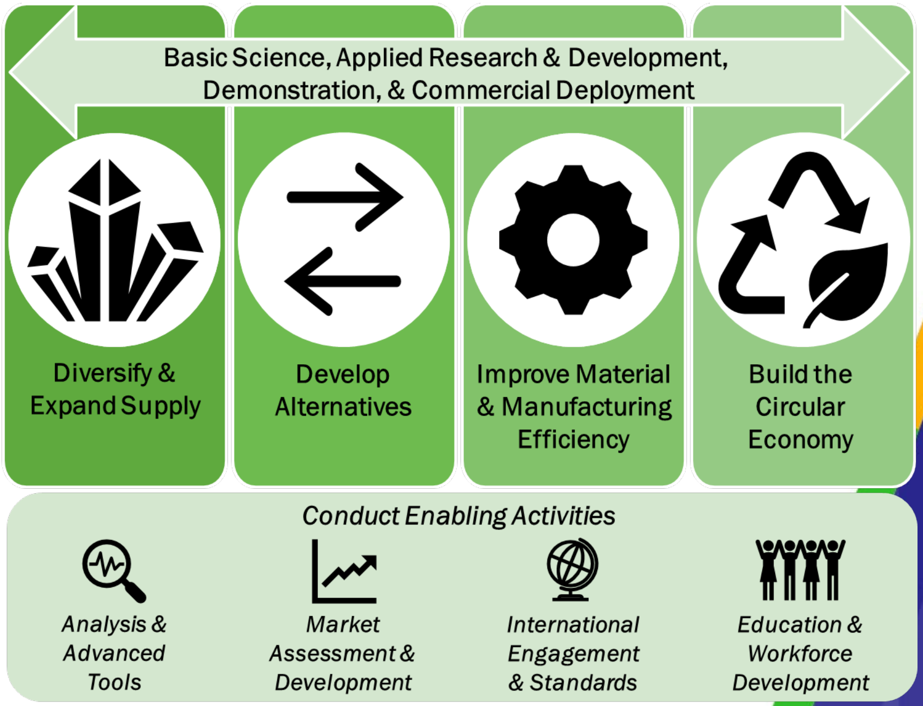
- Building on decades of fundamental materials research, DOE has funded targeted critical minerals and materials (CMM) R&D activities for more than ten years, evolving from a focus on rare earth elements to the current focus on the electric eighteen.
- DOE is now carrying out a **CMM Vision and Strategy** to advance technology development for CMM in the up-, mid-, and downstream portions of clean energy supply chains.

CMM Vision

- Build reliable, resilient, affordable, diverse, sustainable, and secure domestic critical mineral and materials supply chains.
- Promote safe, sustainable, economic, and environmentally just solutions to meet current and future needs.
- Support the clean energy transition and decarbonization of the energy, manufacturing, and transportation economies.

*The **four core pillars** of the CMM Strategy are **supported by crosscutting enabling activities**.*

CMM Strategy



DIVERSIFY AND EXPAND SUPPLY

Identify and secure substantial resources from a wide variety of reliable feedstocks, including recycled electronic waste, wastes from mining and industrial processes, conventional ore bodies, co-produced materials from existing mining, and international partners.

Opportunities informing program development:

- Unconventional feedstocks (e.g., newly mined coal and ionic clays) and secondary materials (e.g., new scrap, coal waste, coal ash, and legacy mine waste) typically have low CMM concentrations but have high potential.
- Recycled materials (old or post-consumer scrap) can reduce pressure on virgin ore supplies. See also the Strategy's fourth pillar: Build the Circular Economy.
- Conventional mining and processing have lost social license in the United States. Advanced technologies with much lighter environmental footprint can improve public confidence while expanding supply.
- Domestic sources are insufficient to meet demand in the short term; in the long term, a diversified network of supply is still prudent. Working with responsible international partners to secure more CMM from more diverse locations helps boost CMM supply resilience.

Unconventional Feedstocks and Secondary Materials

Recycled Materials

Domestic Mining with Advanced Technologies

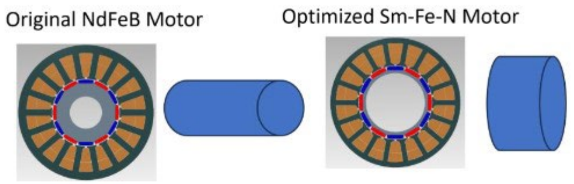
International Sources

DEVELOP ALTERNATIVES

Produce new materials (e.g., alloys) that can be substituted for existing CMM and design manufactured parts and systems that require little to no CMM to function. These alternatives pose less risk of supply chain disruptions.

Opportunities informing program development:

- CMM often have unique properties that are difficult to replace.
  - REE (e.g., neodymium and dysprosium) enable high energy density in magnets.
  - Cobalt provides thermal stability in lithium-ion batteries.
- But materials science can enable partial or complete substitutes for CMM in a material, component, or system.
  - Lanthanum and cerium can partially replace Nd in magnets.
  - Lithium-iron-phosphate EV battery cathodes use no cobalt or nickel.
  - Induction motors are alternatives to permanent magnet EV motors.
- Redesigning end-use system may enable use of non-critical materials with weaker properties while not compromising performance.



Parameters	Optimized / Original designs	
	Original (N33H)	Opti (Sm-Fe-N)
Weight, kg	17.40	13.72
Volume, m^3	0.0028	0.0024
Efficiency (%)	96.40	97.20
Torque ripple (Nm)	11	5.20
Demag. (T)	-2.16	-2.93

CMI researchers from Ames National Lab used a new design tool to devise an optimal motor for less critical Sm-Fe-N magnets (top). The design shows comparable and even improved performance against the original commercial NdFeB magnet (N33H) motor (bottom). (Adapted from CMI Hub 2024.)

IMPROVE MATERIALS AND MANUFACTURING EFFICIENCY

Design materials to make the most of every atom, reduce waste through efficient use, and improve overall efficiency of mining, processing, refining, and manufacturing technologies, systems, and processes.

Opportunities informing program development:

- Engineer for atom economy: Engineer new materials that minimize or eliminate CMM but maintain functionality.
- Minimize resource use: Reduce costs and societal impacts by reducing energy, water, chemical, and other inputs for CMM mining, processing, refining, and manufacturing.
- Minimize environmental impacts: Explore materials and processes with fewer impacts to health and the environment, which can save time and money by improving public perception and aiding the permitting process.
- Increase efficiency: Increase coproduction, separate CMM more selectively, boost near net shape production, etc., to reduce losses of CMM from the mining, processing, and manufacturing waste streams.

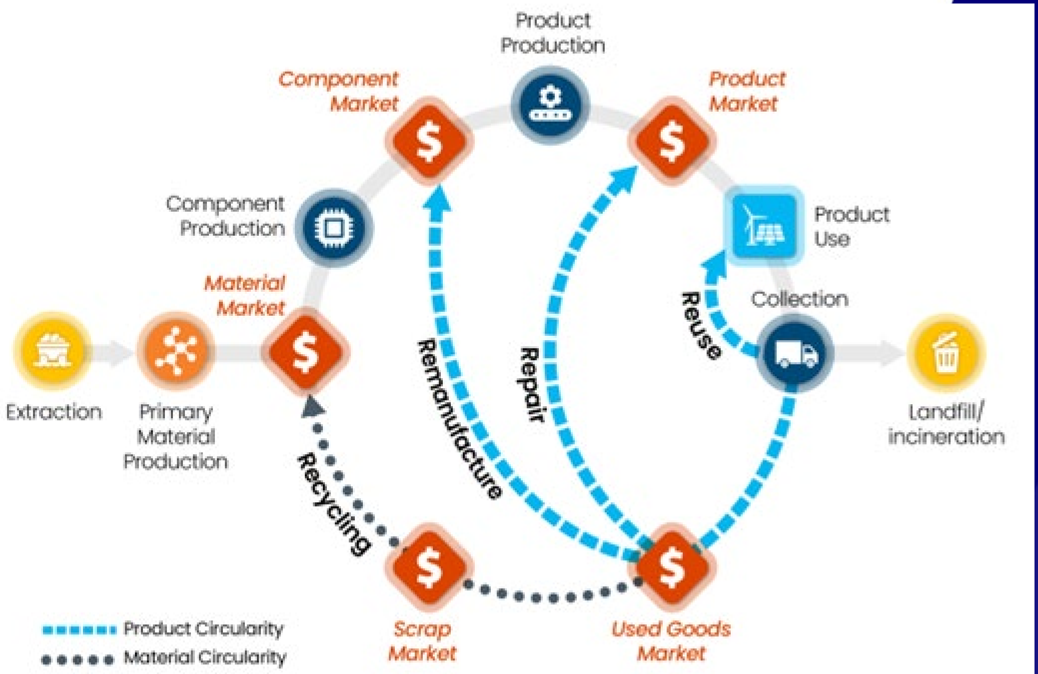
An Idaho National Lab scientist operates a counter-current solvent extraction system for testing and developing an REE separation process design, part of a CMI Hub breakthrough that greatly reduced the number of steps involved in REE separation. (Credit: INL via ORNL.)

BUILD THE CIRCULAR ECONOMY

Remanufacture, refurbish, repair, reuse, recycle, and repurpose all materials to extend the lifetime of materials in use and/or partially offset the need for virgin material extraction.

Opportunities informing program development:

- Give components and systems a second life through reuse or repurposing.
- Use transformative R&D to enable design with reuse and ease of repair in mind.
- Increase recovery from secondary and unconventional materials.
- Minimize waste through improved efficiency and increased coproduction.
- Increase recycling rates (e.g., from end-of-life EVs and offshore wind turbines).
- Increase adoption of recycled materials and refurbished parts.



Conceptual illustration of product and material circularity pathways emphasizing the role of markets in the circular economy. (DOE 2024 in press.)

CONDUCT ENABLING ACTIVITIES

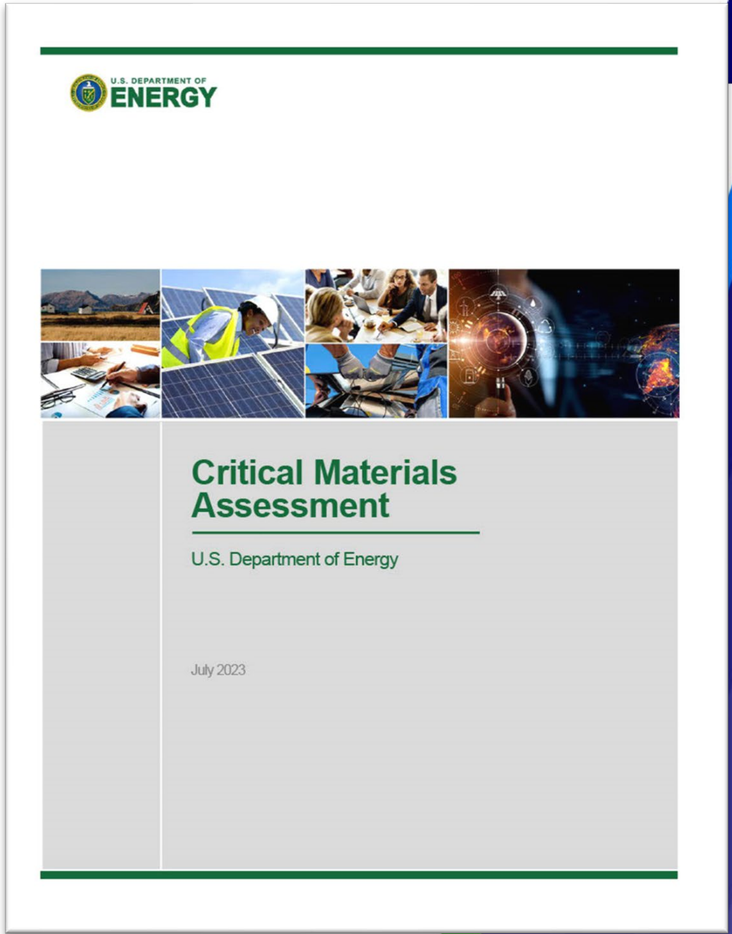
Use vital crosscutting activities to enable and enhance the department's CMM RDD&D efforts across the four strategy pillars.

Conduct Enabling Activities

- *Analysis & Advanced Tools*
- *Market Assessment & Development*
- *International Engagement & Standards*
- *Education & Workforce Development*

Examples of enabling activities include:

- Completion of the Critical Materials Assessment, which informs DOE policy priorities and R&D investment.
- Release of the Critical Materials Market Dynamics Request for Information.
- Collaboration with NIST, EPA, and other agencies to develop effective international standards across the supply chain for CMM production and use.
- Publication of the Education and Workforce Development for CMM Supply Chains Workshop Report.



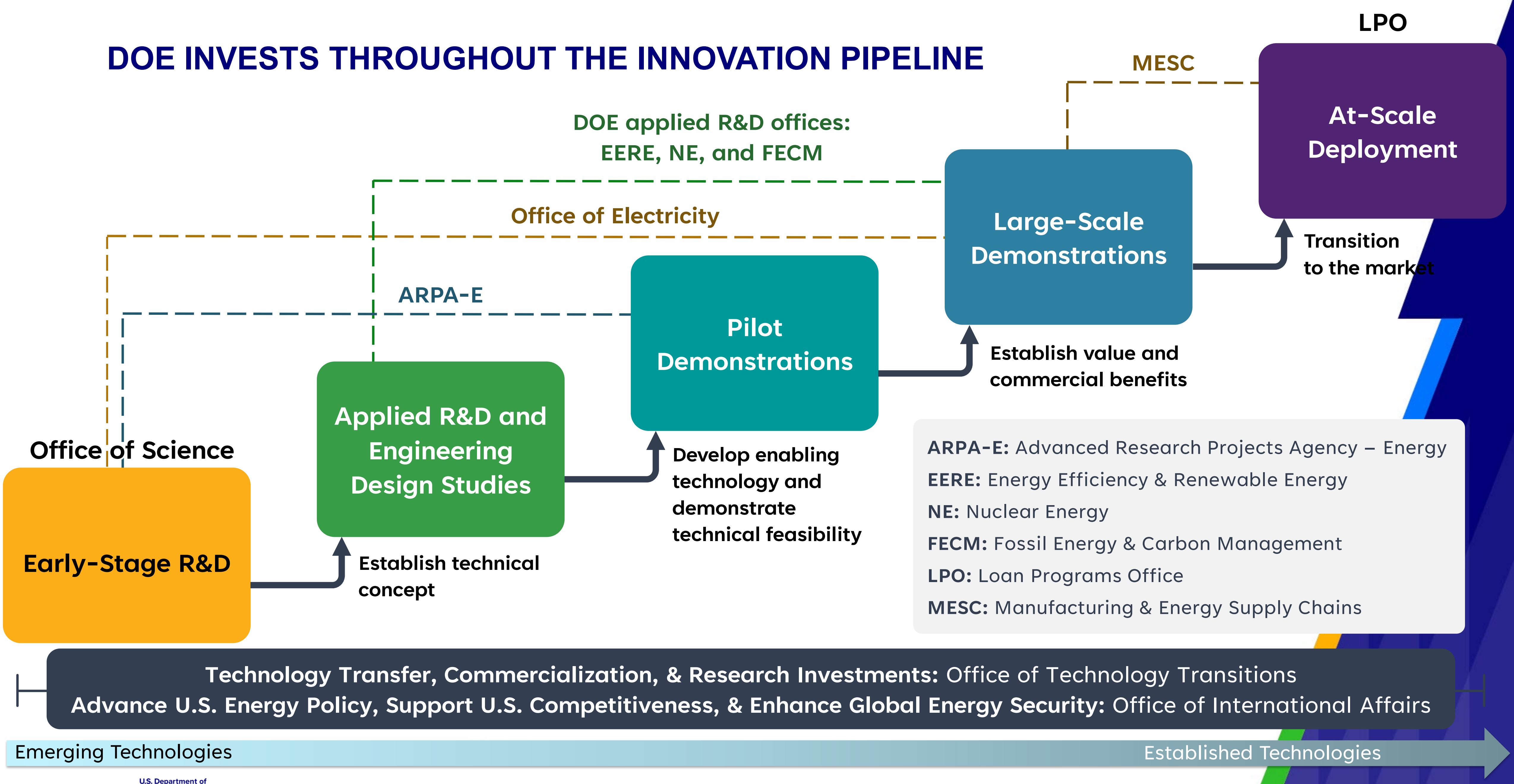
U.S. DEPARTMENT OF ENERGY

Critical Materials Assessment

U.S. Department of Energy

July 2023

DOE INVESTS THROUGHOUT THE INNOVATION PIPELINE



LPO

MESC

DOE applied R&D offices:
EERE, NE, and FECM

Office of Electricity

ARPA-E

Office of Science

At-Scale Deployment

Transition to the market

Large-Scale Demonstrations

Establish value and commercial benefits

Pilot Demonstrations

Develop enabling technology and demonstrate technical feasibility

Applied R&D and Engineering Design Studies

Establish technical concept

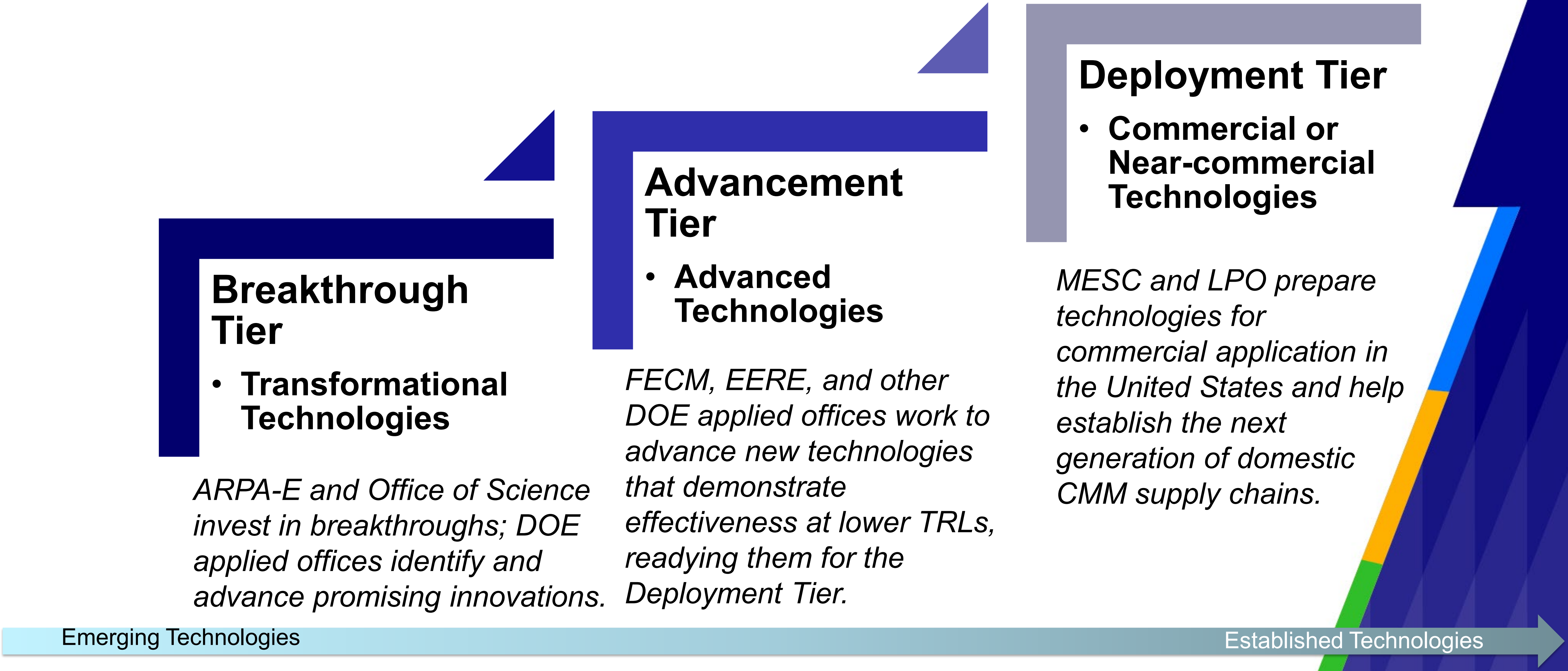
Early-Stage R&D

ARPA-E: Advanced Research Projects Agency – Energy
EERE: Energy Efficiency & Renewable Energy
NE: Nuclear Energy
FECM: Fossil Energy & Carbon Management
LPO: Loan Programs Office
MESC: Manufacturing & Energy Supply Chains

Technology Transfer, Commercialization, & Research Investments: Office of Technology Transitions
Advance U.S. Energy Policy, Support U.S. Competitiveness, & Enhance Global Energy Security: Office of International Affairs

Emerging Technologies → Established Technologies

MULTI-TIERED APPROACH TO TECHNOLOGY DEVELOPMENT



Breakthrough Tier

- **Transformational Technologies**

ARPA-E and Office of Science invest in breakthroughs; DOE applied offices identify and advance promising innovations.

Advancement Tier

- **Advanced Technologies**

FECM, EERE, and other DOE applied offices work to advance new technologies that demonstrate effectiveness at lower TRLs, readying them for the Deployment Tier.

Deployment Tier

- **Commercial or Near-commercial Technologies**

MESC and LPO prepare technologies for commercial application in the United States and help establish the next generation of domestic CMM supply chains.

CMM Technology Development

DOE CRITICAL MINERALS AND MATERIALS PROGRAM

- To carry out the CMM Vision and Strategy, DOE has established the Critical Minerals and Materials Program (CMM Program), which encompasses all DOE CMM research, development, demonstration, and deployment (RDD&D) activities.
- Strategic planning for the CMM Program was informed by federal legislation, executive actions, DOE supply chain analyses, and extensive stakeholder engagement.
- The CMM Program, in alignment with programmatic goals across DOE offices, has four main goals:

1. Create an integrated innovation ecosystem to facilitate rich scientific and technological exchange

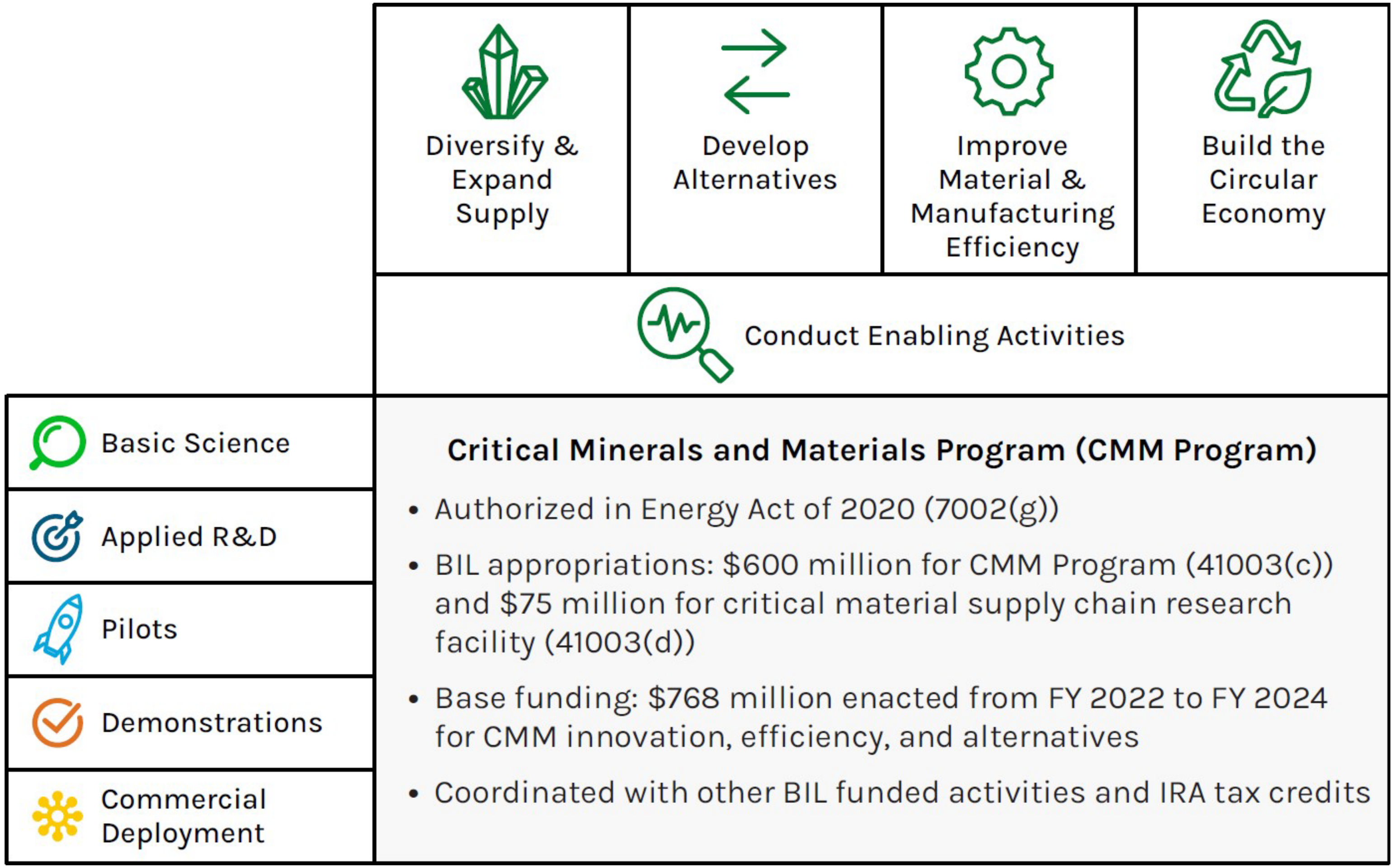
2. Coordinate research to advance environmentally responsible and cost-competitive innovations

3. Work through the interagency to identify and address risks, challenges, and high-impact opportunities

4. Establish and transform the domestic supply chain to secure CMM for the clean energy industrial base

CMM PROGRAM FRAMEWORK

The CMM Program represents the intersection of the innovation pipeline with the four pillars and enabling activities of the CMM strategy:



Diversify & Expand Supply

Develop Alternatives

Improve Material & Manufacturing Efficiency

Build the Circular Economy

Conduct Enabling Activities

Basic Science

Applied R&D

Pilots

Demonstrations

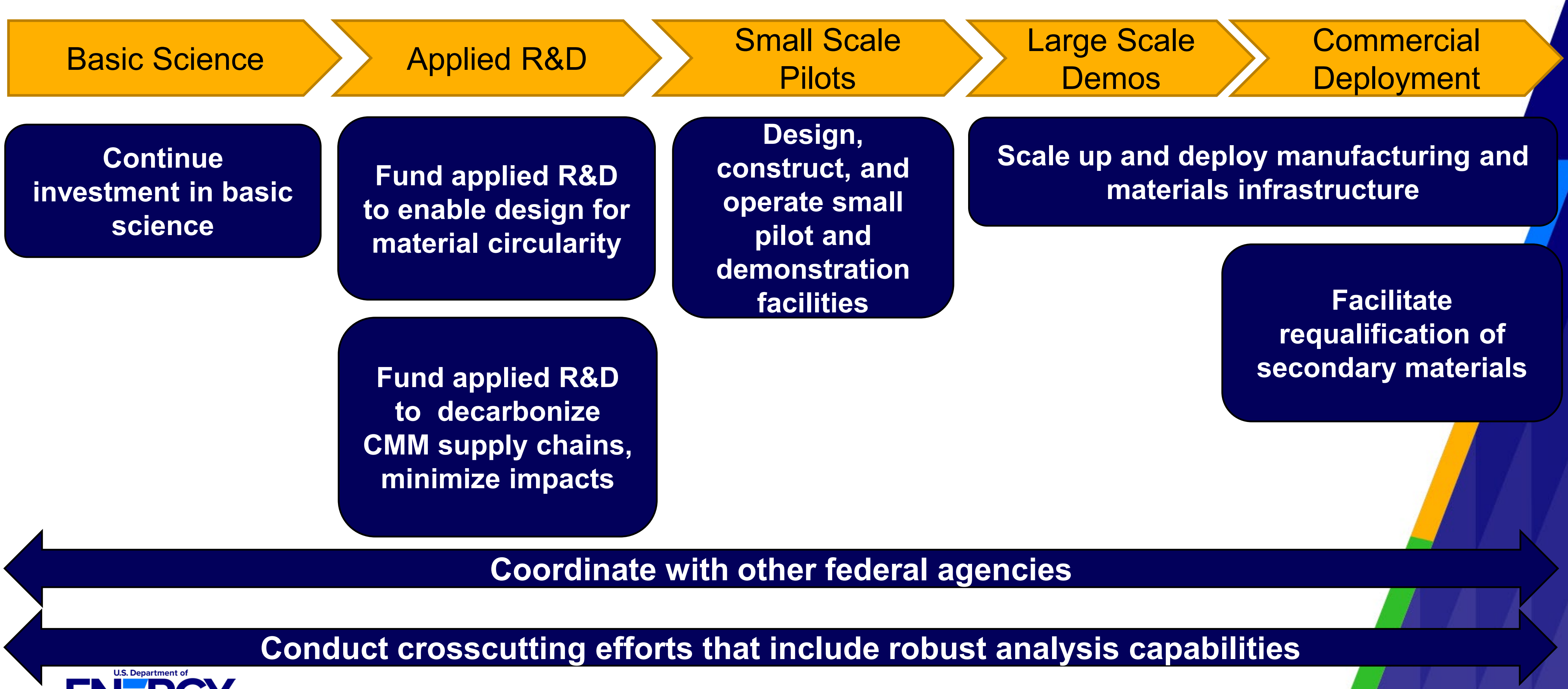
Commercial Deployment

Critical Minerals and Materials Program (CMM Program)

- Authorized in Energy Act of 2020 (7002(g))
- BIL appropriations: $600 million for CMM Program (41003(c)) and $75 million for critical material supply chain research facility (41003(d))
- Base funding: $768 million enacted from FY 2022 to FY 2024 for CMM innovation, efficiency, and alternatives
- Coordinated with other BIL funded activities and IRA tax credits

CMM PROGRAM PRIORITIES

DOE priorities for the CMM Program, spanning the innovation pipeline:



Basic Science

Applied R&D

Small Scale Pilots

Large Scale Demos

Commercial Deployment

Continue investment in basic science

Fund applied R&D to enable design for material circularity

Fund applied R&D to decarbonize CMM supply chains, minimize impacts

Design, construct, and operate small pilot and demonstration facilities

Scale up and deploy manufacturing and materials infrastructure

Facilitate requalification of secondary materials

Coordinate with other federal agencies

Conduct crosscutting efforts that include robust analysis capabilities

CRITICAL MATERIALS COLLABORATIVE (CMC)

DOE has launched the CMC in support of the CMM Program.

The CMC is the connective tissue within the DOE CMM Program and the U.S. government, aligning DOE’s RD&D portfolio with DOE climate goals and accelerating adoption of innovative solutions.

Building a robust **innovation ecosystem**.

Training the critical materials leaders and workforce across multiple sectors.

Enabling **industry adoption** of novel, cutting-edge technology.

Laying the **scientific and technological groundwork** needed to address emerging challenges.

CMC RD&D ROADMAP DEVELOPMENT

Purpose: To guide DOE RD&D efforts in critical materials over the next 10 years.

Expected Outcomes: Determine research objectives, enabling the CMC to identify technical goals and milestones for the CMM Program.

Broad Categories for Future RD&D

- New Domestic Sources of CMM
- Advanced Primary CMM Recovery
- Enhanced Processing
- Alternative and Substitute Materials
- Sensors, Field Detectors, and Analytical Methods
- Computational Chemistry, Machine Learning, and Artificial Intelligence
- Circular Economy
- Improved Manufacturing.

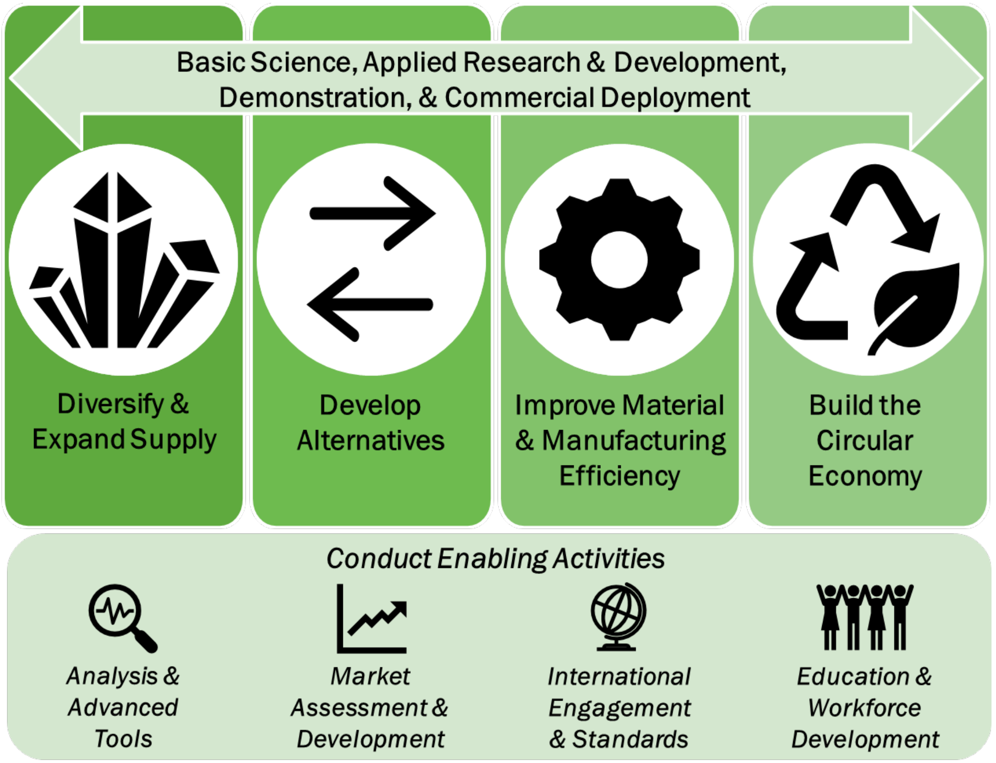
Reach out to cmc@hq.doe.gov to get involved.

(Credit: Microsoft 365 stock image.)

CMM STRATEGY PILLARS IN PRACTICE

As DOE builds the CMM Program, actions within and across CMM Strategy pillars are already:

- Accelerating development of domestic critical materials supply chains.
- Bolstering the clean energy transition.



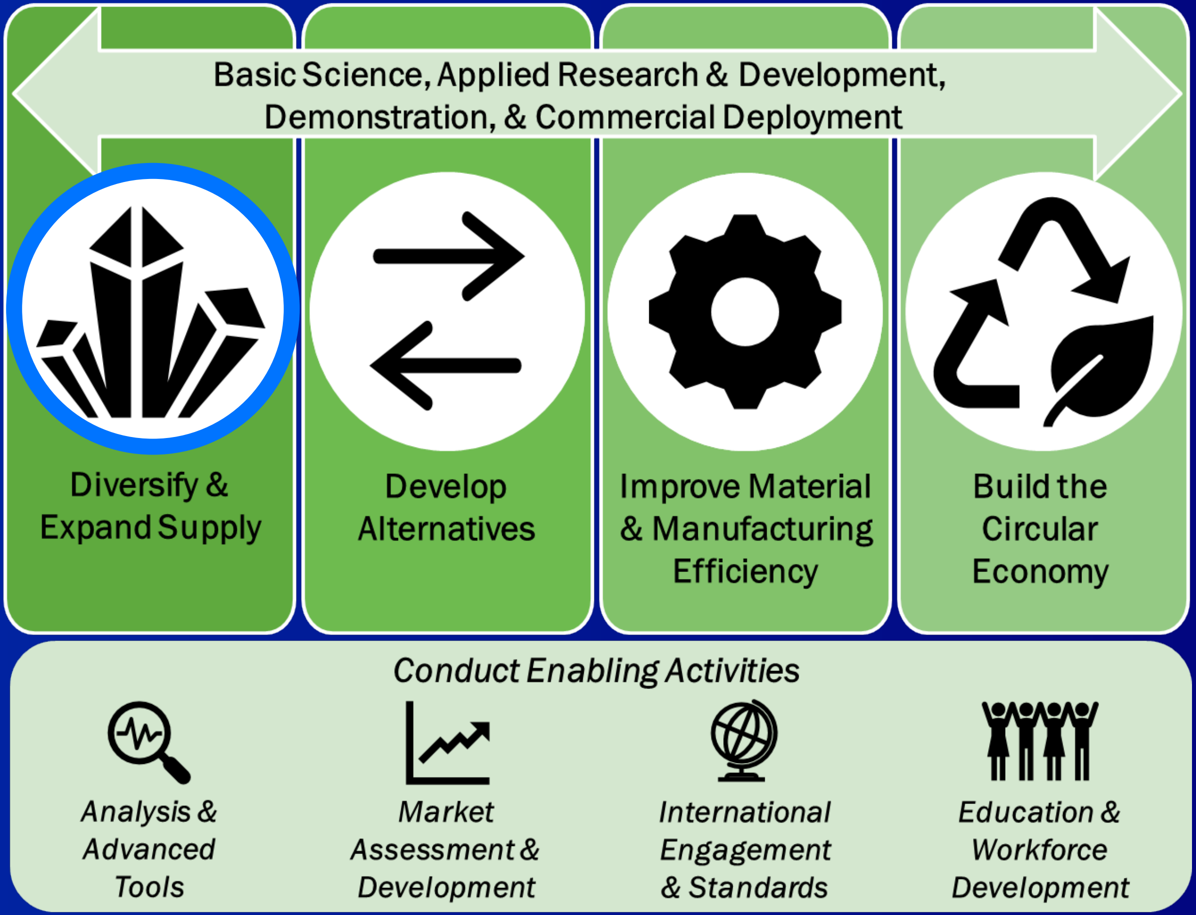
- Making breakthrough scientific discoveries.
- Scaling promising technologies.
- Innovating more efficient manufacturing processes.
- Building circular economy pathways for CMM.

- Publishing criticality assessments and supply chain deep dives.
- Promoting interagency and international cooperation.
- Partnering with institutions of higher education to prepare the next generation of scientists and engineers.

Next: Selected examples of DOE's CMM activities that are making an impact.

DIVERSIFY AND EXPAND SUPPLY

Diversify and Expand Supply



Basic Science, Applied Research & Development, Demonstration, & Commercial Deployment

Diversify & Expand Supply

Develop Alternatives

Improve Material & Manufacturing Efficiency

Build the Circular Economy

Conduct Enabling Activities

Analysis & Advanced Tools

Market Assessment & Development

International Engagement & Standards

Education & Workforce Development

DISCOVERING NEW CHEMISTRY FOR RARE EARTH SEPARATION

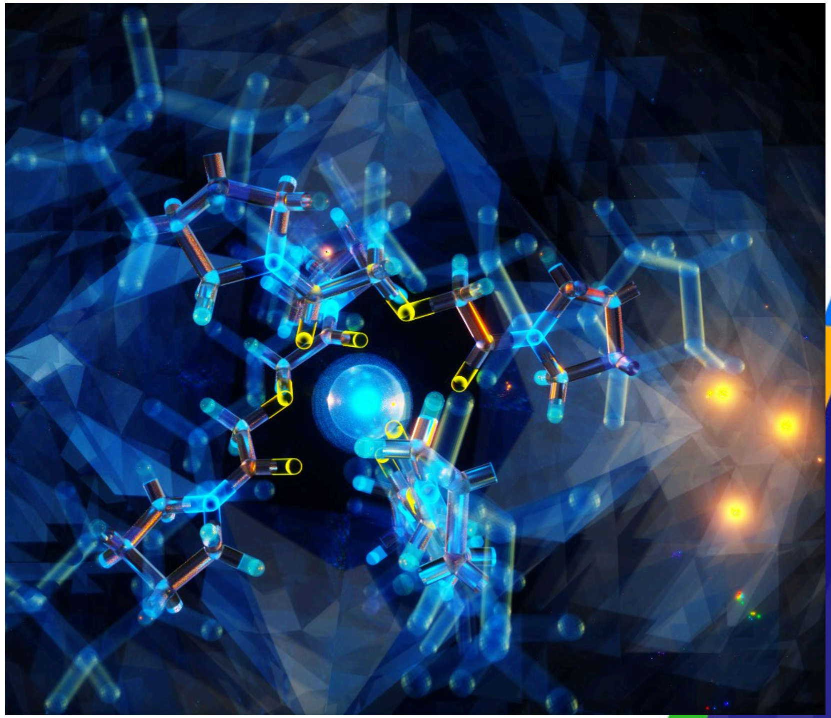
Identifying ways to improve extraction of REE in solution

Achievement

- First investigation of the rarest REE, promethium, binding with diglycolamide (PyDGA) ligand in solution.

Significance and Impact

- Better understanding of “bond contraction” in REE (promethium, neodymium, praseodymium, dysprosium, terbium).
- Improves fundamental understanding of REE in solution.
- May lead to improved selectivity for extracting REE.



Structure of promethium ion bound by water-soluble ligand (PyDGA).
(Credit: Driscoll et al. 2024)

DETERMINING THE CONTROLLING FACTORS OF ORE FORMATION

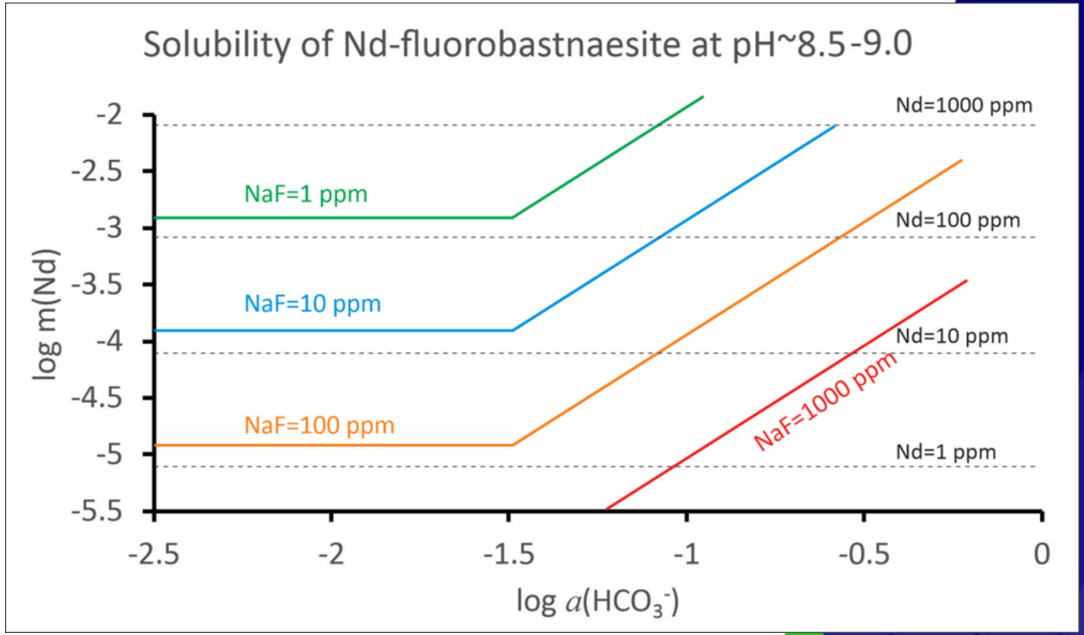
Revealing a mechanism controlling formation of REE ore (bastnäsite)

Achievement

- Study determined that the concentration of fluoride, dictated by the mineral solubility, is a controlling factor in bastnäsite deposit formation.
- Even at moderate fluoride levels, bastnäsite can form.

Significance and Impact

- Bastnäsite is an abundant rare earth ore in North America.
- Although other factors controlling its formation remain uncertain, this study permits quantitative evaluation of the conditions that lead to bastnäsite formation in the presence of fluoride.



Solubility of bastnäsite as a function of carbonate concentration in the solutions containing various background fluoride. (Credit: Reece et al. 2023, Migdisov et al. in prep for *PNAS*.)

MODELING INCREASED MOBILIZATION OF REE MINERALS IN CARBONATE DEPOSITS > 400°C

Identifying REE mobilization mechanisms for natural, carbonate-bearing systems

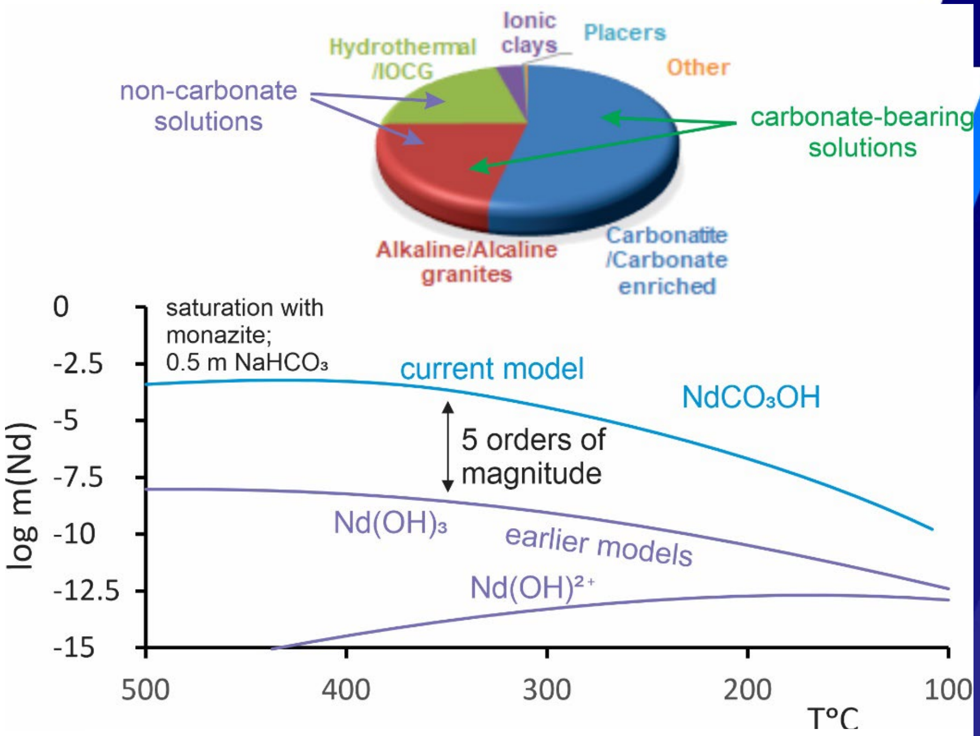
Achievement

- Subsurface transport of neodymium (Nd) in carbonate-bearing solutions is controlled by carbonate complexes.
- The data collected allowed modeling of up to 600°C. Found that at temperatures above 400°C, the solubility of Nd bearing minerals increases drastically (counter to past assumptions).

Significance and Impact

- First quantitative characterization of mobilization and deposition of Nd in carbonatite-related* REE deposits (which comprise ~70% of current sources).

*Carbonatite is an igneous rock composed of greater than 50% carbonate minerals.



Upper: REE deposits by source of rock and association with carbonate-bearing solutions. *Lower*: Comparison of newly found mobilization mechanism with theoretical predictions. (Source: Nisbet et al. 2022; Pan et al. 2024; Migdisov et al. 2024; Reece et al. in prep for *Nat. Comm.*)

UNLOCKING CMM FROM CO_2-REACTIVE ROCK

Mining Innovations for Negative Emissions Resource Recovery (MINER) Program

Achievement

- Injection of CO_2-infused water into ultramafic rock at newly discovered Ni-Co-PGE ore body, replacing CO_2-reactive rock waste with carbonate.
- Chemical reaction-driven cracking of the rock will reduce the energy needed for extraction and comminution (crushing and grinding) 50% or more.

Significance and Impact

- Will reduce the energy needed for critical mineral separation, improve the concentrate grade, and increase ore recovery.
- When ore is exhausted, the mine will live on as a C-sink.

Sample of serpentinite, an ultramafic rock. According to USGS, serpentinite is a likely candidate for carbon storage through mineralization.
(Credit: James St. John/Flickr via USGS.)

EXPANDING DEPLOYMENT THROUGH COMMERCIAL-SCALE FACILITIES

Manufacturing components for EV batteries

Achievement

- Syrah Technologies, a producer of natural graphite-based active anode material (AAM) in lithium-ion batteries, will expand its AAM facility in Louisiana.

Significance and Impact

- Will be the only vertically integrated, large-scale AAM manufacturing facility outside China.
- Expanded capacity is expected to produce AAM for enough EVs to save 52 million gallons of gasoline annually.

CRITICAL MATERIALS

SYRAH VIDALIA

VIDALIA, LOUISIANA

The first battery-grade natural graphite active anode material supplier in the U.S., supporting the growing EV industry.

DIRECT LOAN

$102 MILLION

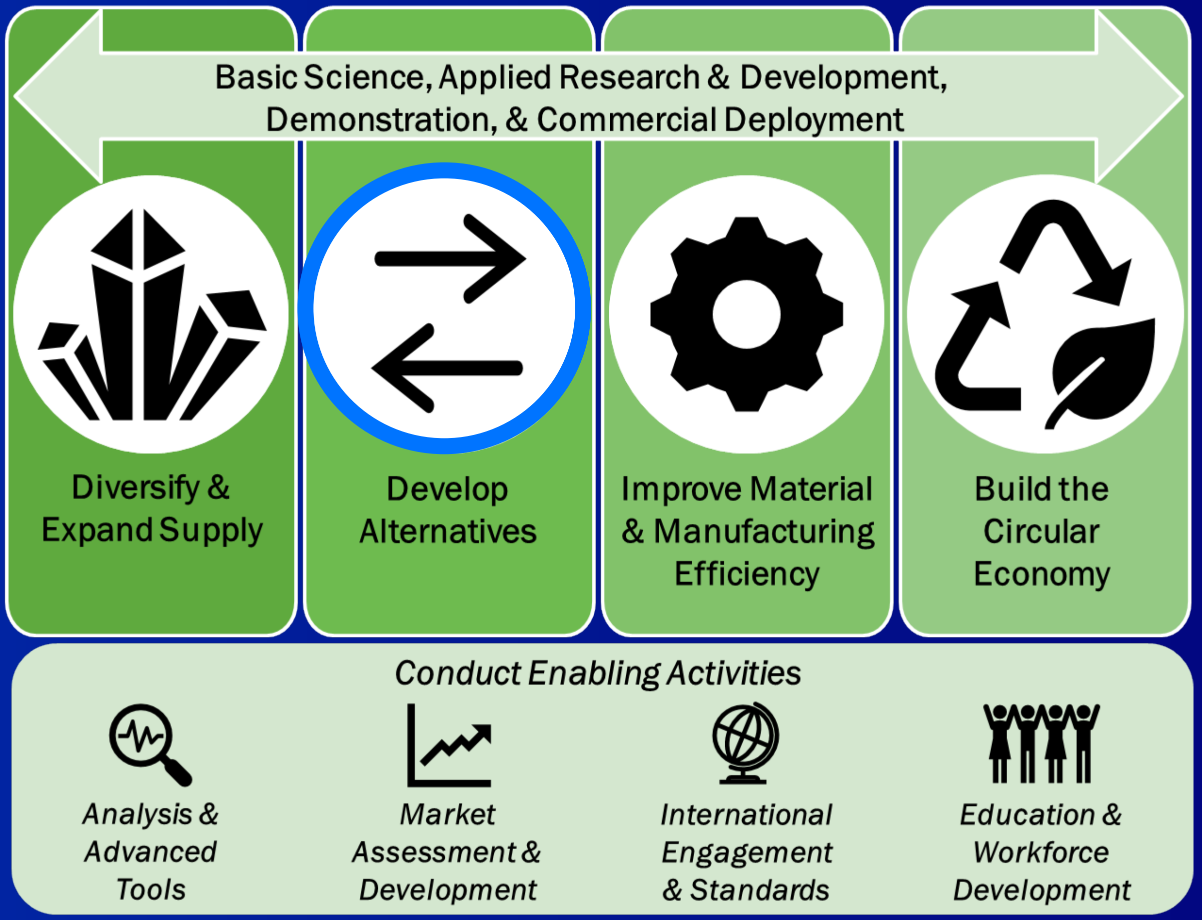
JULY 2022

FINANCED BY U.S. DEPARTMENT OF ENERGY

LPO Loan Programs Office

Announcement of direct loan for expansion of AAM manufacturing facility in Vidalia, LA. (Credit: LPO.)

DEVELOP ALTERNATIVES



Basic Science, Applied Research & Development, Demonstration, & Commercial Deployment

Diversify & Expand Supply

Develop Alternatives

Improve Material & Manufacturing Efficiency

Build the Circular Economy

Conduct Enabling Activities

Analysis & Advanced Tools

Market Assessment & Development

International Engagement & Standards

Education & Workforce Development

USING X-RAYS TO ANALYZE A SINGLE ATOM FOR THE FIRST TIME

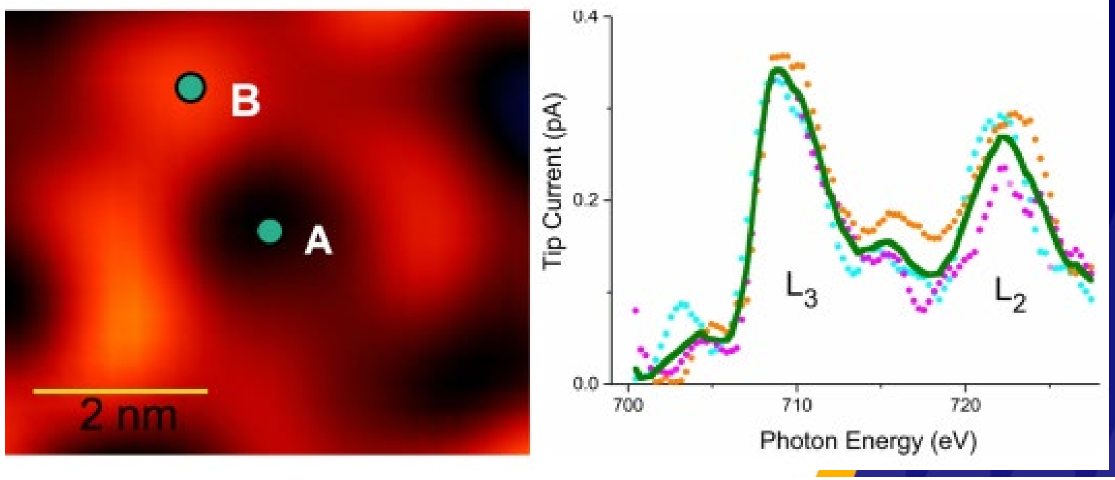
Understanding material properties at the micro-Scale

Achievement

- Combination of synchrotron X-rays with scanning tunneling microscopy to detect the elemental and chemical fingerprint of a single iron atom.
- Same technique used to characterize a single atom of the critical rare earth metal terbium, which is used in magnets for EV motors and wind turbine generators.

Significance and Impact

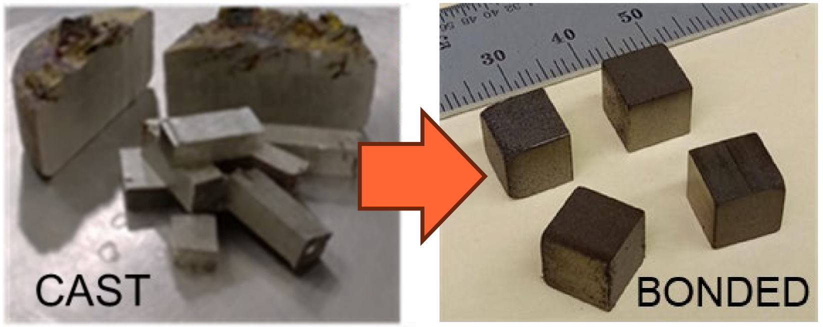
- Breakthrough enables further innovation in materials science and CMM analysis.



Left: Image of a ring-shaped molecular host that contains just one iron atom. *Right*: X-ray absorption spectrum of single atom detected at location B in the molecular ring. Spectrum matches that of iron. (Credit: Argonne National Laboratory.)

CERIUM-BASED "GAP MAGNETS": OFFSETTING NDFEB MAGNET DEMAND

Valorizing surplus cerium to address the rare earth element balance problem



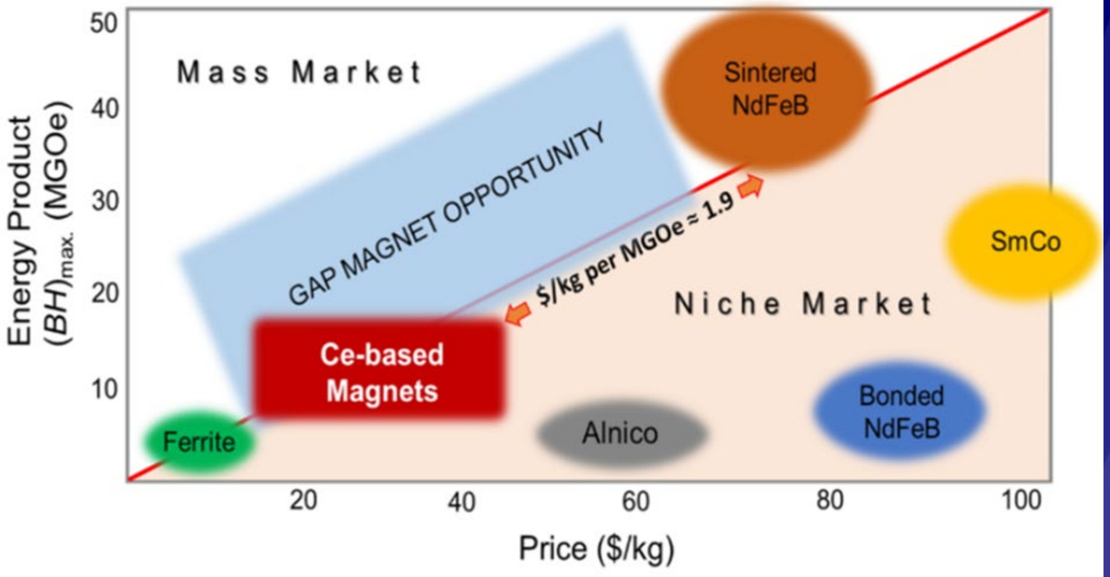
2023 R&D 100 WINNER

Achievement

- One-step process (casting) developed to fabricate cerium-based compression-molded, bonded magnets on a kilogram scale.

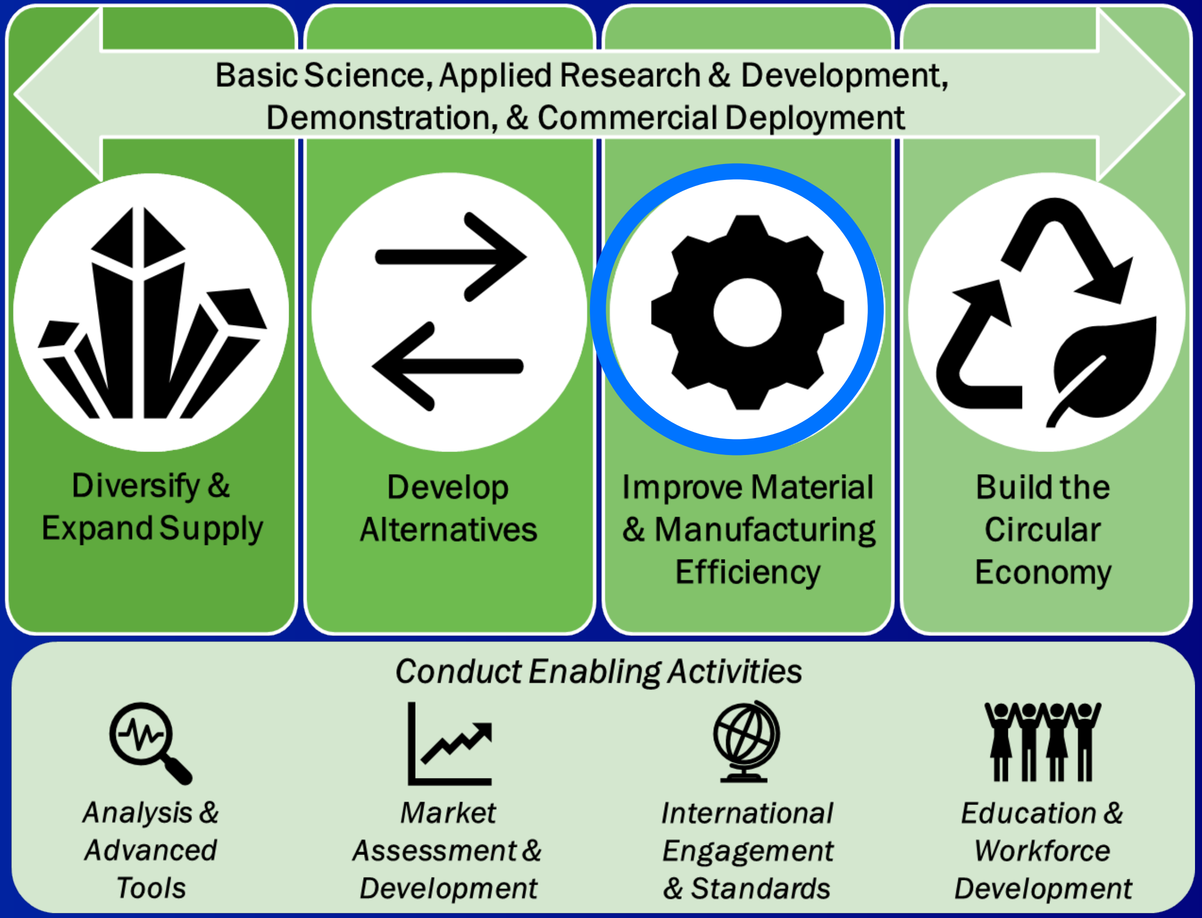
Significance and Impact

- Can partially offset the demand for neodymium iron boron (NdFeB) magnets in mid-strength end-uses ("gap magnets").
- Have potential to create new markets for cerium and improve overall economics of rare earth element mining.



Schematic explanation of the gap magnet opportunity. (Credit: CMI Hub.)

IMPROVE MATERIAL AND MANUFACTURING EFFICIENCY



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MOVING BEYOND CONVENTIONAL SOLVENT-EXTRACTION-BASED SEPARATION

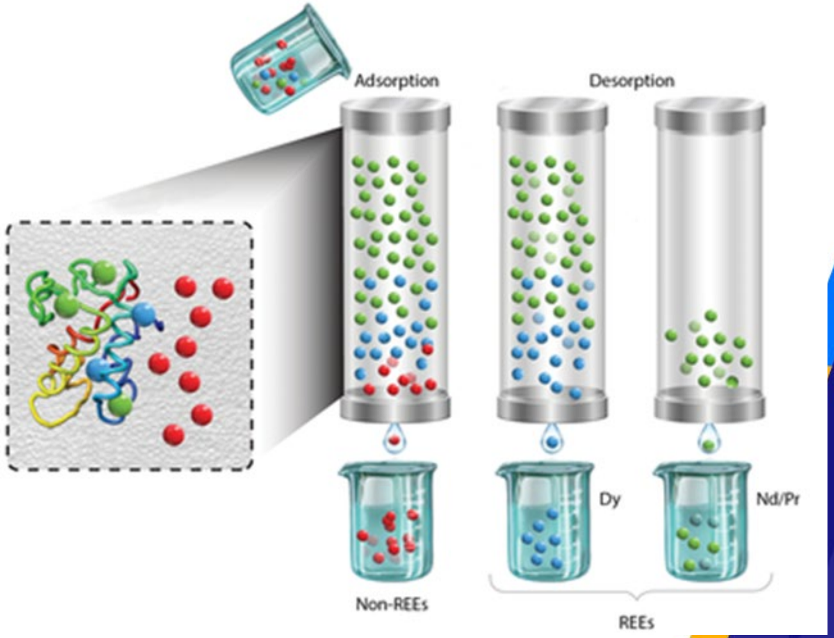
Optimizing REE separation efficiency

Achievement

- Use of the REE-binding biological ligand lanmodulin to reduce the number of separation steps.
- Working with feedstocks that have REE concentrations as low as 1–2%.

Significance and Impact

- Streamlining REE extraction and separation makes the process easier, less time consuming, and less energetically and chemically intensive.



A depiction of the use of REE-binding biological ligand lanmodulin (proteins shown in left-hand box) to significantly reduce the number of separation steps. (Credit: LLNL.)

MANUFACTURING NANOGRAIN MAGNETS: CONTINUOUS HOT ROLL PROCESS

Increasing cost-competitiveness through simplified processing

Achievement

- Development of NdFeB based magnets strong and heat-resistant enough to eliminate critical dysprosium from an alloy mixture.

Significance and Impact

- Traditional production involves an expensive two-step batch process that requires tools and vacuum furnaces, but the process has been simplified to one continuous step.
- Saves time, money, and energy in making nanograin magnets.

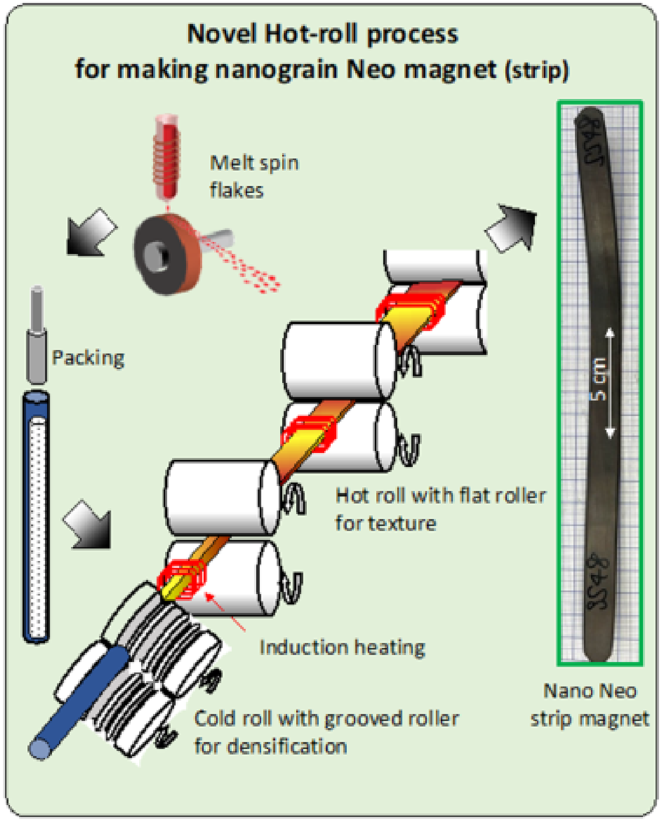
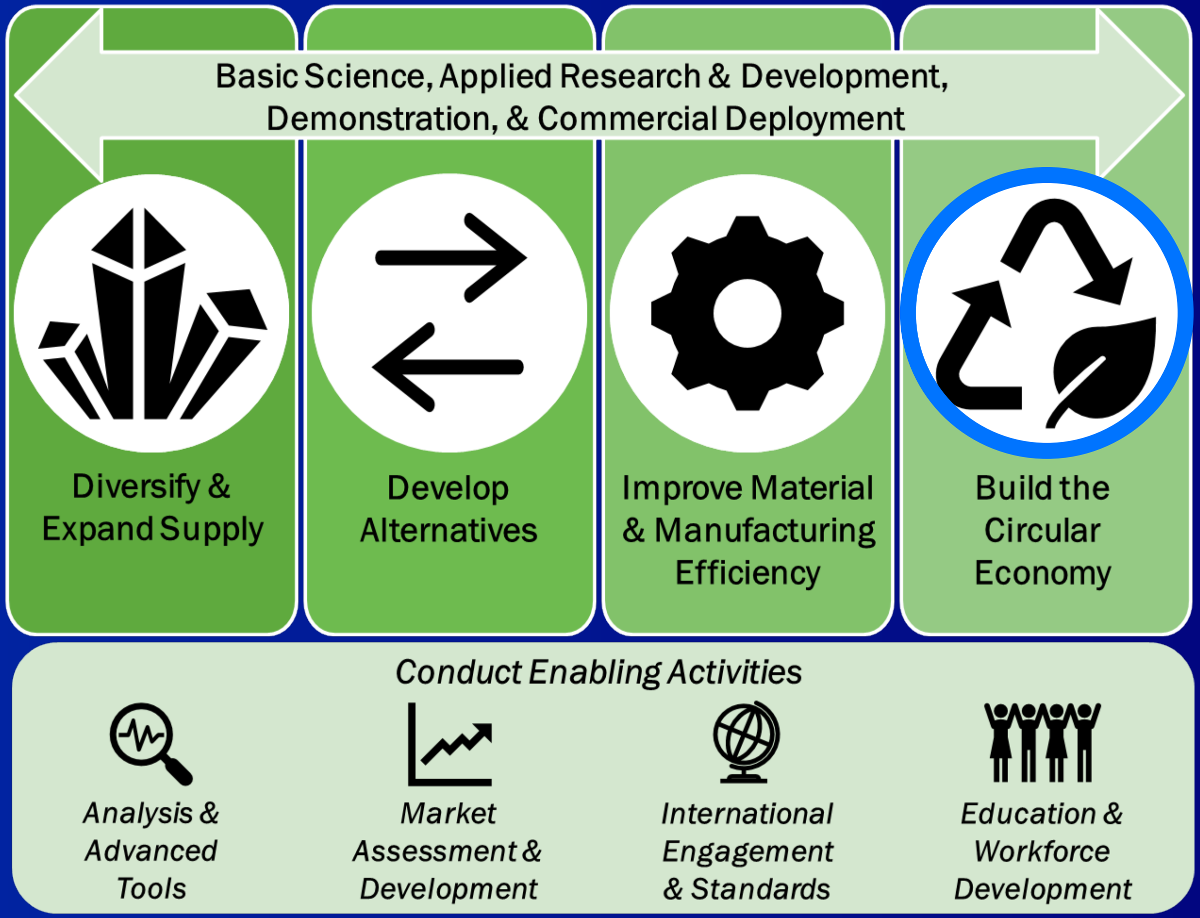


Diagram of novel hot-roll process for making nanograin magnet. (Credit: CMI Hub.)

2023 R&D 100 WINNER

BUILD THE CIRCULAR ECONOMY



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BOOSTING CIRCULARITY WITH THE WIND TURBINE MATERIALS RECYCLING PRIZE

Advancing recycling of magnets from land-based wind farms

Achievement

- Prize was launched to address the bulk of wind turbine materials that are not currently commercially recyclable in the United States, including critical dysprosium, neodymium, praseodymium, and terbium.
- Selected teams will develop prototypes in Phase 2; six teams will win cash prizes and vouchers to work with DOE national labs.

Significance and Impact

- Spurring innovation will help create a more circular economy for the U.S. wind industry.

In January 2024, DOE announced 20 winners from 15 states for the first phase, with each receiving $75,000. (Credit: WETO.)

U.S. Department of ENERGY

EXPANDING U.S. BATTERY RECYCLING AND CMM PROCESSING

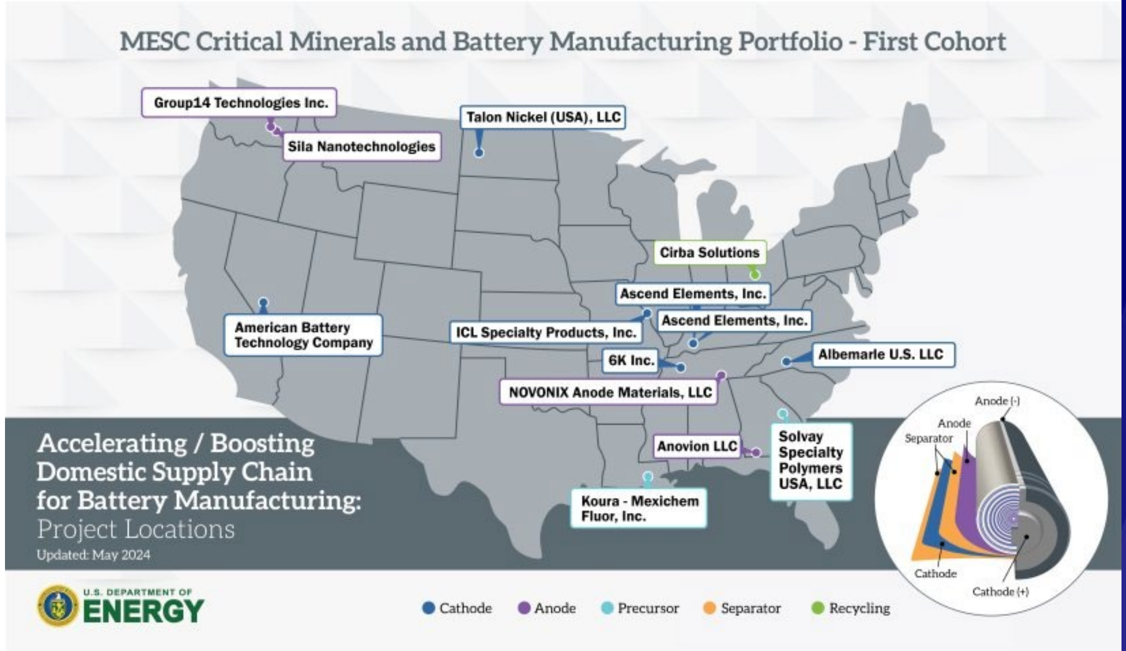
Enabling a more robust domestic battery supply chain

Achievement

- Companies will build or expand commercial-scale facilities to separate and process battery CMM; recycle batteries; and manufacture battery components from recycled materials.

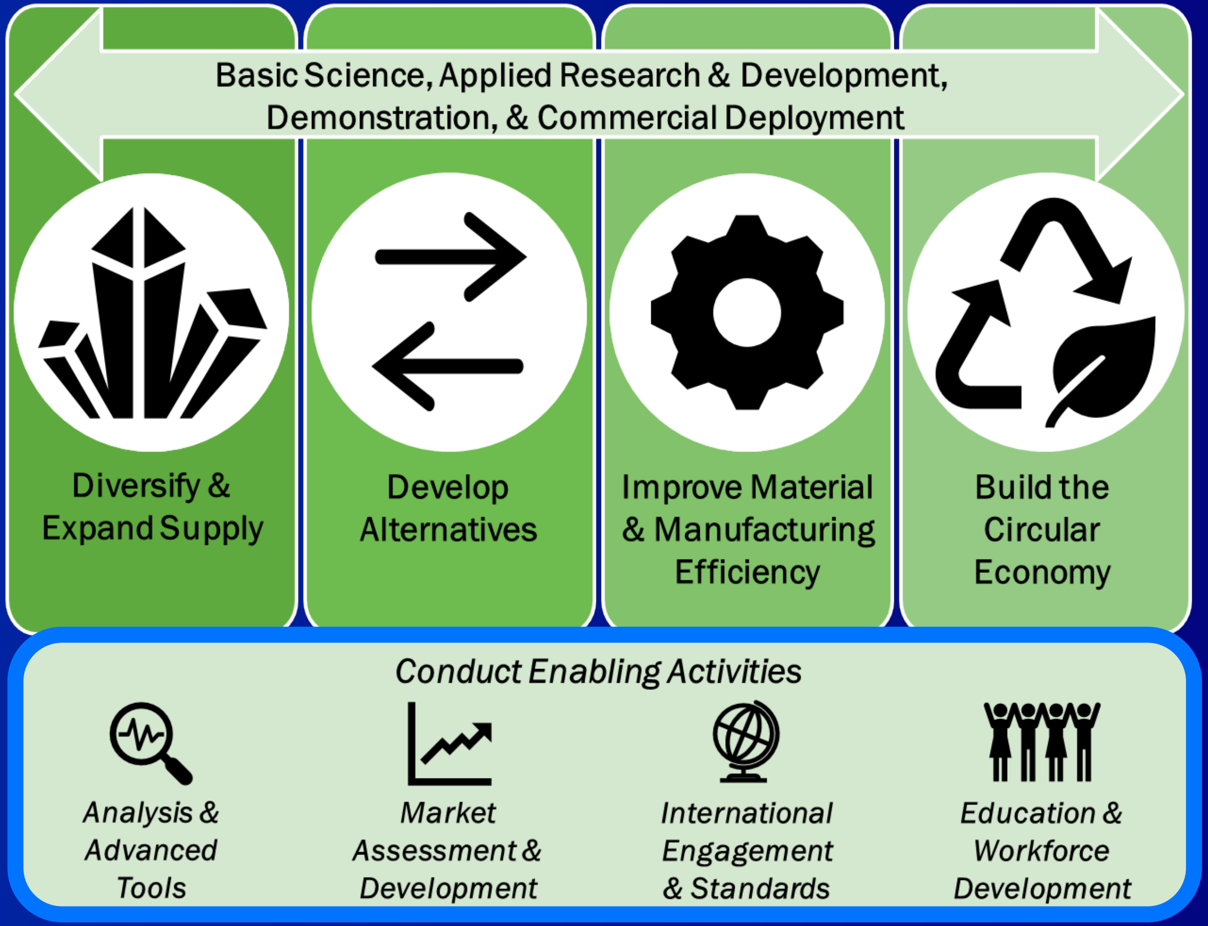
Significance and Impact

- One Ohio facility turns end-of-life LIB into battery-grade raw materials. Its expansion will produce enough CMM for battery cathodes to supply more than 200,000 new EVs per year.
- These circularity enhancements will boost U.S. battery supply chain security.



MESC Critical Minerals and Battery Manufacturing Portfolio. (Credit: DOE MESC.)

ENABLE CROSSCUT ACTIVITIES



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PROVIDING WORLD-CLASS SCIENTIFIC USER FACILITIES

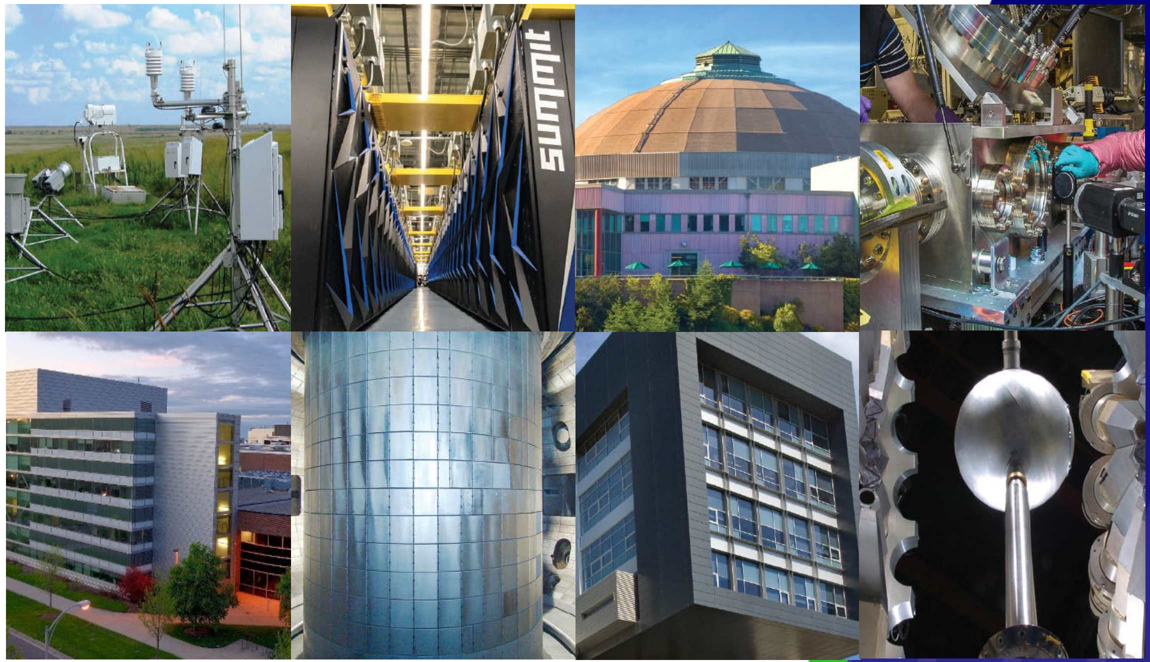
Supplying tools and expertise to further scientific development

Achievement

- DOE funds the construction, maintenance, and advancement of world-leading X-ray, neutron, nanoscience, and high-performance computing user facilities.

Significance and Impact

- Facilities provide advanced synthesis, fabrication, characterization, and computational capabilities for basic, applied, and industrial research.
- Facilities help train the next generation of scientists.



Collage of several DOE laboratory facilities.
(Source: DOE Office of Science.)

U.S. Department of ENERGY

DETERMINING CRITICAL MATERIALS FOR ENERGY

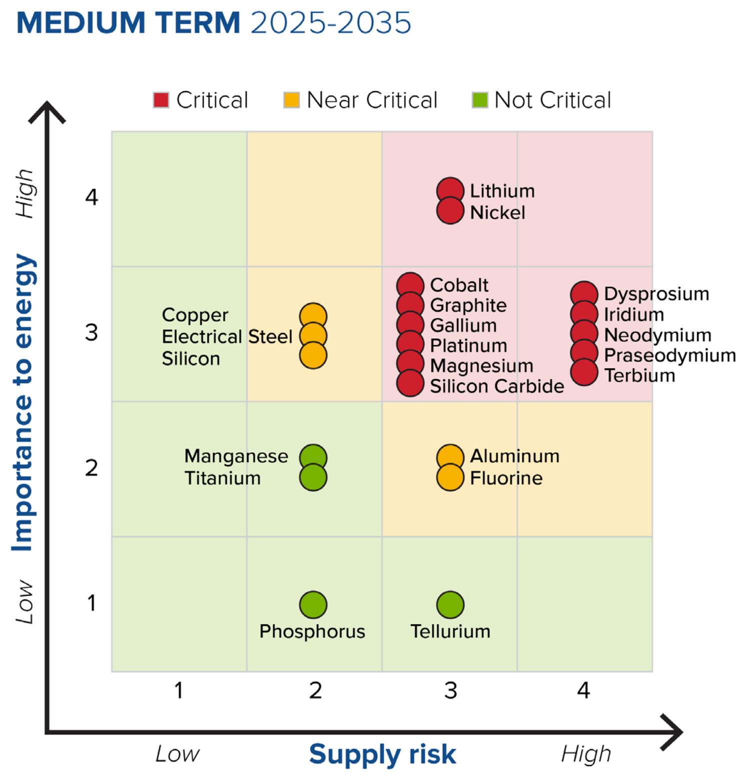
Publishing the 2023 Critical Materials Assessment and Critical Materials List

Achievement

- The 2023 Critical Materials Assessment evaluated materials for their importance to global clean energy technology supply chains.
- Based on the report's results, DOE determined the Electric Eighteen, or critical materials for energy.

Significance and Impact

- Assessment enables DOE to set priorities for CMM RDD&D and develop an integrated strategy to address material-specific risks.



MEDIUM TERM 2025-2035

Medium Term Criticality Matrix from the 2023 Critical Materials Assessment. Yellow and red dots indicate the Electric Eighteen critical materials for energy. ([DOE 2023](DOE 2023))

U.S. Department of ENERGY

DEPLOYING THE BATTERY WORKFORCE INITIATIVE

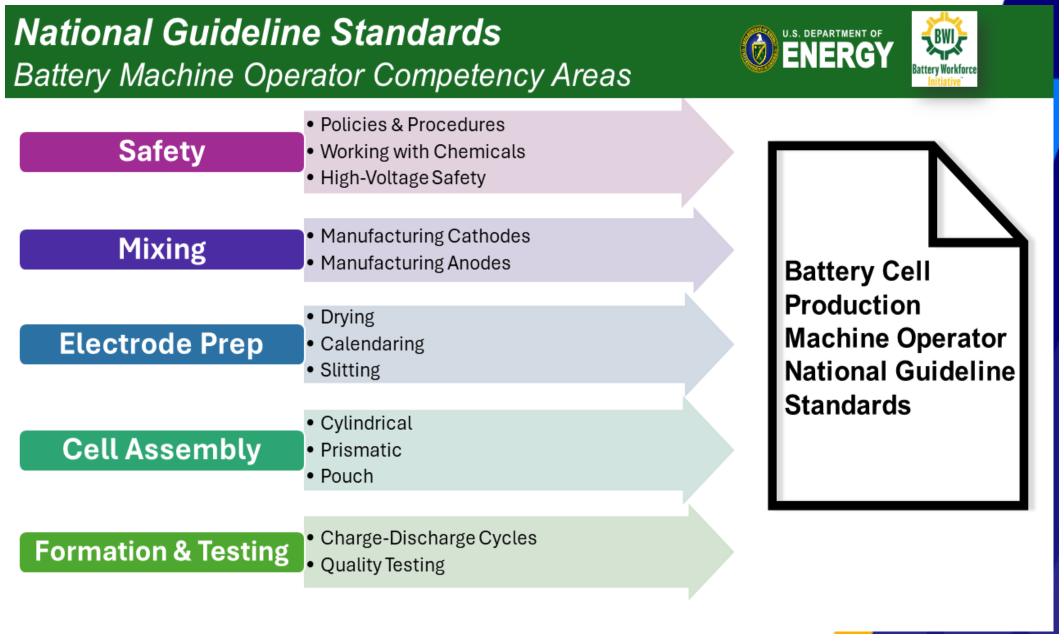
Training the current and future workforce for advanced batteries

Achievement

- Industry-driven, government-facilitated initiative develops training and materials for key jobs in the advanced battery industry, complementing ongoing workforce development efforts.

Significance and Impact

- Initiative will accelerate the development of high-quality training for key battery related occupations.
- BWI seeks to create a consensus on core training needs, then develop training for use by companies and local providers.



National Guideline Standards

Battery Machine Operator Competency Areas

- **Safety**
  - Policies & Procedures
  - Working with Chemicals
  - High-Voltage Safety
- **Mixing**
  - Manufacturing Cathodes
  - Manufacturing Anodes
- **Electrode Prep**
  - Drying
  - Calendaring
  - Slitting
- **Cell Assembly**
  - Cylindrical
  - Prismatic
  - Pouch
- **Formation & Testing**
  - Charge-Discharge Cycles
  - Quality Testing

Battery Cell Production Machine Operator National Guideline Standards

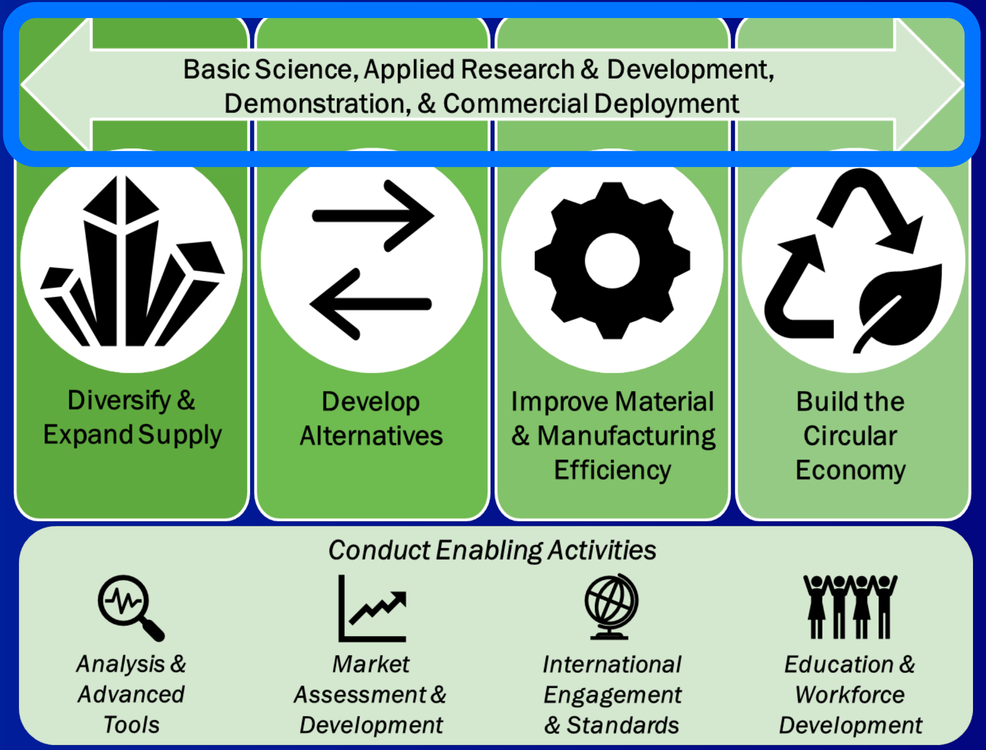
The Battery Workforce Initiative finalized the National Guideline Standards (NGS) for the Battery Machine Operator occupation, providing a detailed list of skill requirements and competencies. (Credit: NETL/BWI.)

EXAMPLES OF SUCCESS SPANNING THE INNOVATION PIPELINE

DOE connects innovation across offices and builds pathways that advance solutions to market.

Sustained and coordinated DOE funding drives advancements up and down the innovation pipeline, from basic science to commercial deployment. Three vignettes follow that illustrate DOE's impact:

1. **Cost-Effective Rare Earth Element Separation**
2. **Membrane Solvent Extraction: Advanced Battery Recycling**
3. **CMM Processing from Domestic Waste Resources.**



COST-EFFECTIVE RARE EARTH ELEMENT SEPARATION

Public-private consortium enables translation of basic science to support development of real-world solutions to meet industry needs

Basic Science

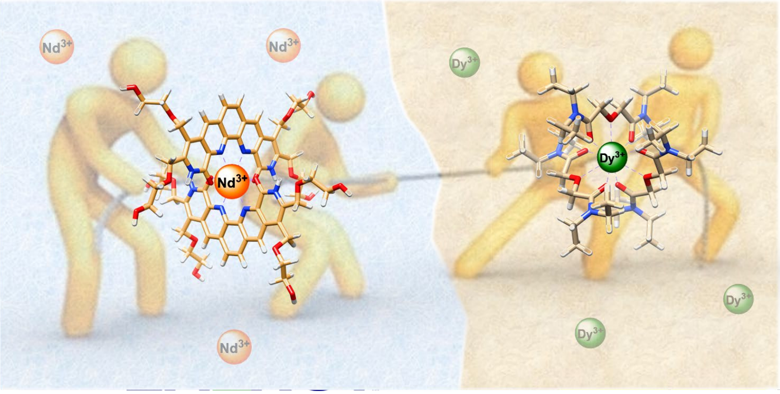
- CMI Hub developed new strategies for REE separation discovered through computation modeling and X-ray adsorption spectroscopy.

Applied R&D

- CMI Hub designed novel ligands/extractants that show improved separation of rare earth elements, outperforming the industry standard, with potential to reduce the cost and footprint of the separation process.

Technology Commercialization

- Industry partner licensed the technology and is working to commercialize the production of the novel ligands to meet the needs of a variety of companies.



MEMBRANE SOLVENT EXTRACTION: ADVANCED BATTERY RECYCLING

Prior R&D investments have positioned DOE to mature and deploy innovative technologies

Applied R&D

- CMI Hub scientists developed a modular, cost-effective recycling alternative called Membrane Solvent Extraction (MSX) to transform black mass into separated battery materials.

Large Scale Deployment

- Cirba Solutions is advancing a novel integrated end-to-end processing of end-of-life EV batteries for remanufacturing of new EV cells.
- Momentum Technologies is partnering with Cirba Solutions to *deploy MSX* to separate intermediate mixed-metal sulfate into *pure-battery-grade nitrates* needed for battery cathode manufacturing.

CMM Processing from Domestic Waste Resources

Maturing Rare Earth Element (REE) Recovery from Legacy Coal Waste from Pilot To Demonstration Scale

PRODUCTION

PROCESSING

PROSPECTING

TRL 3-5

2016: Conventional REE Separation & Recovery: 80-90% Purity

2017: Transformational Separation

TRL 5-7

2019: Three First-of-a-Kind Bench & Small Pilot-Scale REE Facilities

2020: REE System Optimization & Efficiency Improvements – CMM Production

2020 & 2021: Concept & Feasibility Studies

2021: Advanced Processing Phase 1

TRL 5-7

2021 & 2022: Two Additional First-of-a-Kind Small Pilot-Scale REE & CMM Facilities

TRL 7-8

2023: REE Demonstration Facility (Phase 1)

Enabled by BIL

2027-2028: First-of-a-Kind REE Demonstration Facility (Phase 2)

1,000 tonnes Mixed REOs per year & CMM through Metals Refining

First-of-kind pilot for REE recovery from acid mine drainage

2015 2020 2025

FISCAL YEAR 2025 BUDGET REQUEST

Critical Minerals and Materials Funding by Appropriation and Program Control ($k)

Appropriation and Program Control	FY 2022 Enacted	FY 2023 Enacted	FY 2024 Enacted	FY 2025 Request
Advanced Research Projects Agency – Energy	42,170	5,010	10,000	-
Energy Efficiency and Renewable Energy	112,523	157,900	166,748	192,172
Advanced Manufacturing Office (AMO)	47,000	26,000	-	-
Advanced Materials and Manufacturing Technologies Office (AMO successor office)	-	-	50,000	50,000
Geothermal Technologies	50	3,000	2,248	2,787
Hydrogen and Fuel Cell Technologies	30,000	30,000	14,000	22,000
Solar Energy Technologies	-	16,000	4,000	10,000
Vehicle Technologies	34,000	73,700	96,500	107,385
Wind Energy Technologies	1,473	9,200	0	0
Fossil Energy and Carbon Management	23,000	44,000	70,000	74,000
Minerals Sustainability	23,000	44,000	70,000	74,000
Nuclear Energy	61,500	-	*	-
Fuel Cycle Research and Development	60,500	-	-	-
Nuclear Energy Enabling Technologies	1,000	-	-	-
Office of Technology Transitions	100	-	-	-
Science	25,000	25,000	25,000	25,000
Basic Energy Sciences	25,000	25,000	25,000	25,000
Manufacturing and Energy Supply Chains	-	-	-	34,350
Manufacturing Capacity and Competitiveness	-	-	-	28,350
Supply Chain Mapping, Modeling & Analysis	-	-	-	6,000
Grand Total	264,293	231,910	271,748	325,522

U.S. Department of ENERGY

*NE's request for FY24 funding was for work related to uranium. Section 7002(a) of the Energy Act of 2020 restricts the listing of critical materials to "any non-fuel mineral, element, substance, or material." Based on the DOE Critical Materials Assessment, which includes only use of uranium as a fuel, DOE did not designate uranium as a critical material.

CATALYZING PROGRESS FOR DOMESTIC CMM SUPPLY CHAINS

Prior to BIL/IRA, DOE CMM efforts were generally focused on ***fundamental discovery and R&D for new and novel technologies***.

- DOE helped ***build the foundation*** of next-generation technology that is environmentally and technically sustainable in the United States.

Post-BIL/IRA, DOE has established offices and ***long-term funding for commercialization and deployment*** of large-scale processing projects.

- BIL is ***maturing technologies*** developed through prior R&D investments.

DOE-funded commercial battery materials projects via MESC and LPO ***can support 20-40% of EV battery mineral demand by 2030***.

- These projects include recycling, harvesting from alternate feedstocks, direct lithium extraction, and other highly innovative and sustainable methodologies.

DOE investments have ***unlocked over $1 billion in private investment*** for CMM supply chains.

- The catalytic effect of federal funding helps enable the use of domestic CMM for domestic manufacturing.

The DOE-led **CMC—the new, growing coalition coordinating CMM applied RD&D—will build on this success** and accelerate progress toward secure, sustainable CMM supply chains and a clean energy future.

U.S. Department of ENERGY

ENGAGE

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more about DOE's Critical Minerals and Materials Program

www.energy.gov/cmm/critical-minerals-materials-program

Reach Out

with questions, comments, or engagement inquiries

cmc@hq.doe.gov

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KEY RESOURCES FOR FURTHER READING

"What are Critical Materials and Critical Minerals?" (DOE 2023)

Critical Materials Assessment (DOE 2023)

America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition (DOE 2022)

Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-based Growth (The White House 2021)

Critical Materials: Action Needed to Implement Requirements That Reduce Supply Chain Risks (U.S. GAO 2024)