U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

ADVANCED MATERIALS & MANUFACTURING TECHNOLOGIES OFFICE

Innovations for the Magnet Supply Chain

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Advanced Materials & Manufacturing Technologies Office (AMMTO)

January 17, 2024

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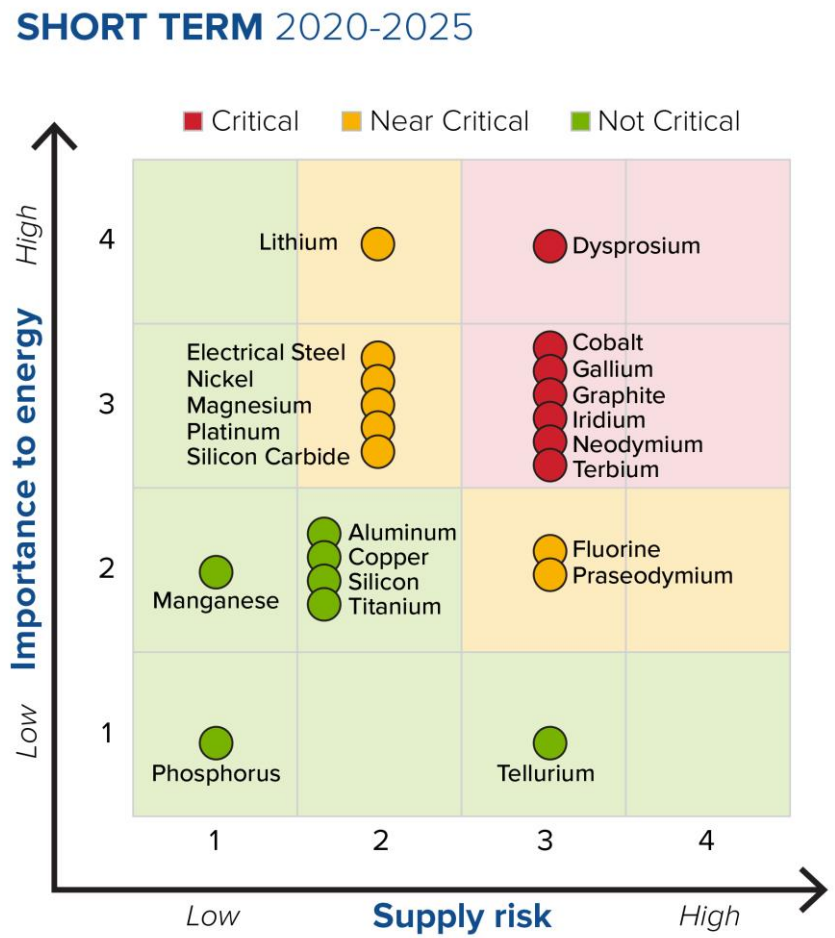
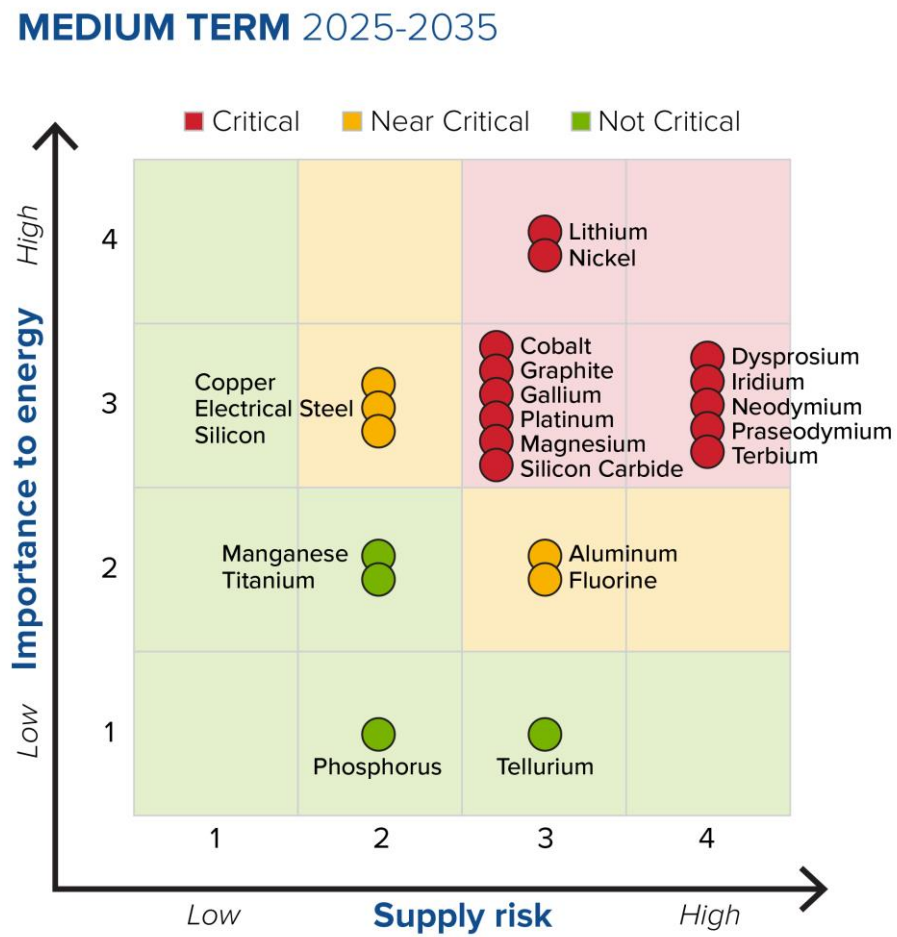
What are critical materials?

- Critical materials are materials that have high risk for supply disruption and serve an essential function in one or more energy technologies





https://www.energy.gov/cmm/what-are-critical-materials-and-critical-minerals

The "Electric Eighteen": Critical Materials Vital for the Clean Energy Transition

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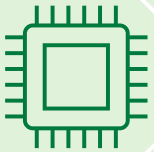
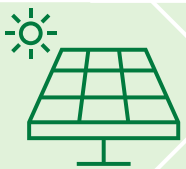
Neodymium, Praseodymium, Dysprosium & Terbium		**Magnets** for wind turbine generators & EV motors
Cobalt, Lithium, Graphite, Nickel, Graphite & Fluorine		**Batteries** for electric vehicles & grid storage
Iridium & Platinum		**Electrolyzers** for green hydrogen production & **fuel cells** for energy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

Climate Goals

- 100% clean electricity by 2035
- Net-zero economy by 2050

Clean Tech Deployment Goals

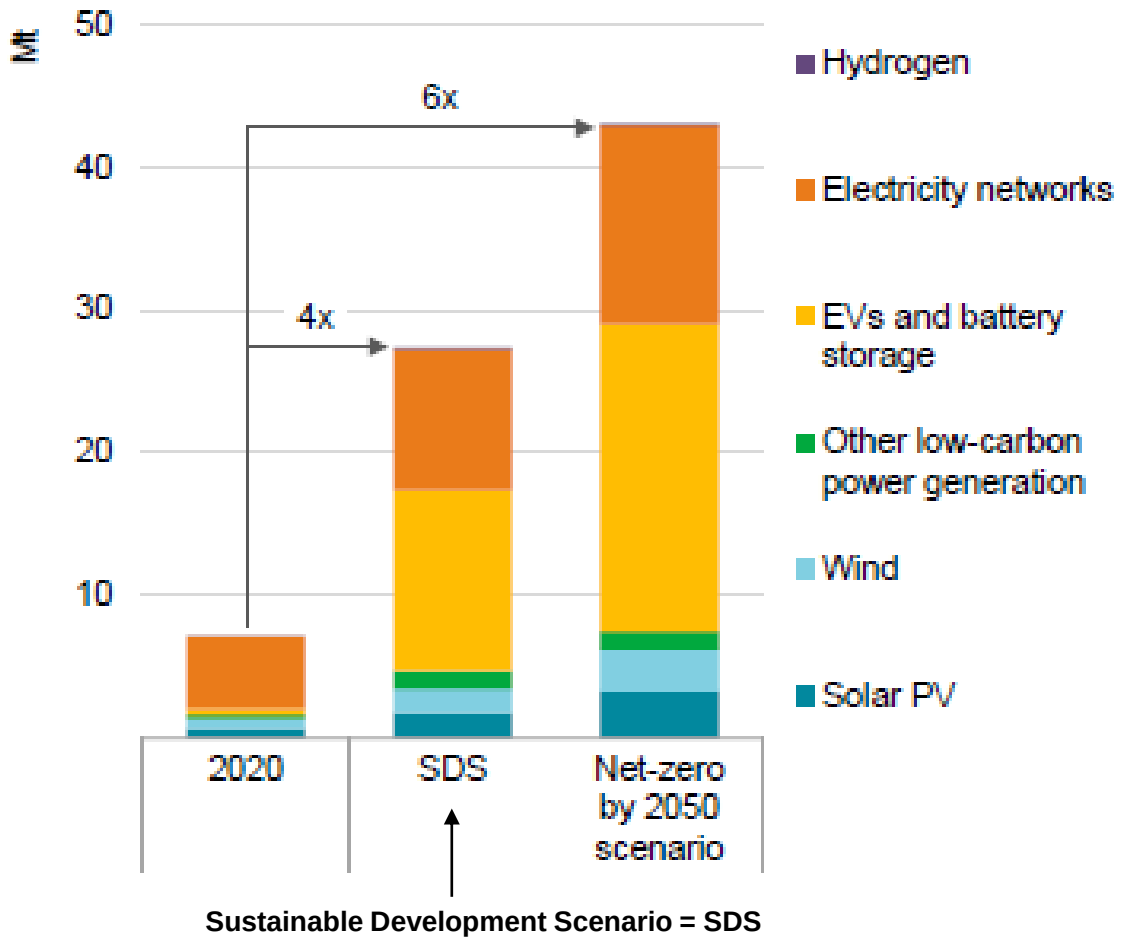
- 50% ZEV sales by 2030
- 30 GW offshore wind by 2030
- Cost of Clean Hydrogen $1/kg by 2031

*Not on the USGS Critical Minerals List

Critical Materials Demand Driven by Decarbonization Goals

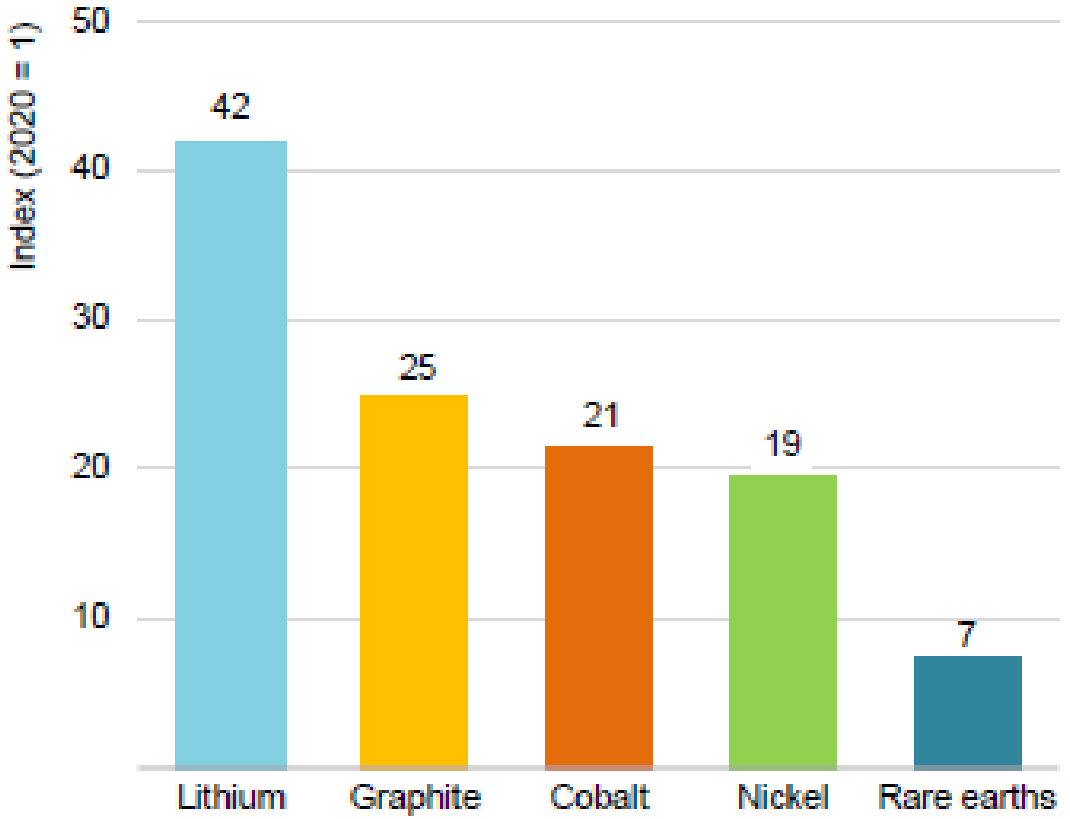
Mineral demand for clean energy technologies by scenario

Growth to 2040 by sector



Sustainable Development Scenario = SDS

Growth of selected minerals in the SDS, 2040 relative to 2020



Notes: Mt = million tonnes. Includes all minerals in the scope of this report, but does not include steel and aluminium. See Annex for a full list of minerals.

Source: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/

DOE Critical Minerals & Materials (CMM) Vision & Strategy

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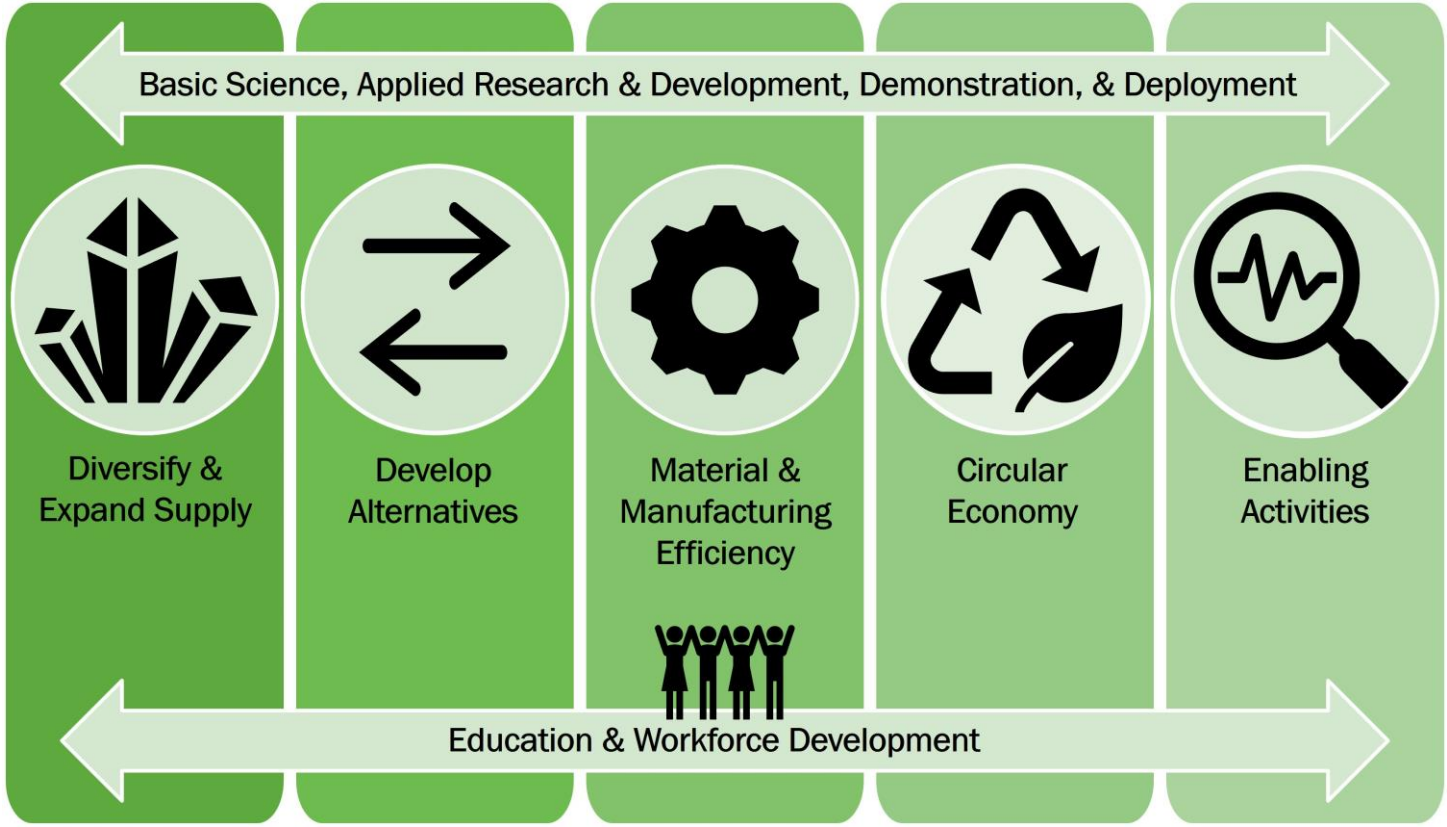
Vision:

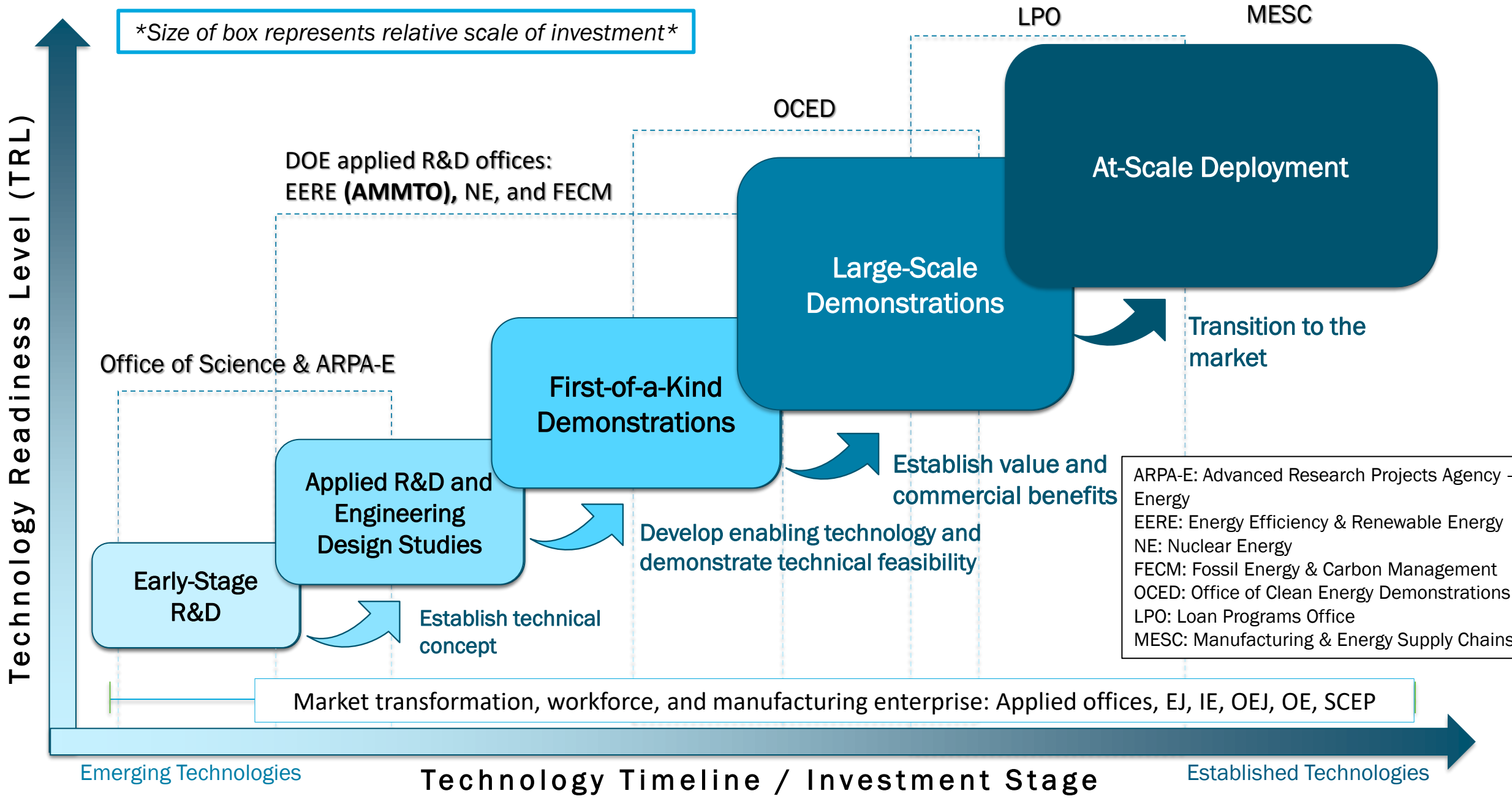
- **Reliable, resilient, affordable, diverse, sustainable, and secure domestic critical mineral and materials supply chains**
- Support the clean energy transition and decarbonization of the energy, manufacturing, and transportation economies
- Promote safe, sustainable, economic, and environmentally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

CMM Strategies:



https://www.energy.gov/critical-minerals-materials

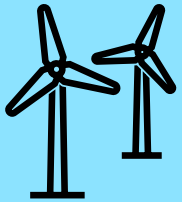
DOE is an integral part of an All-of-Government Strategy



AMMTO's Subprogram Structure

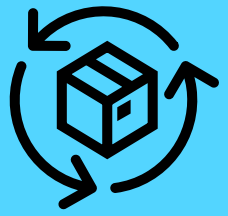
NEXT-GENERATION MATERIALS & PROCESSES

Advanced Manufacturing Processes and Systems



High Performance Materials

SECURE & SUSTAINABLE MATERIALS

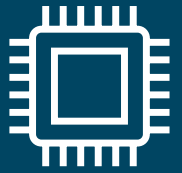


Circular Economy Technologies and Systems

Critical Materials

ENERGY TECHNOLOGY MANUFACTURING & WORKFORCE

Energy Conversion and Storage Manufacturing



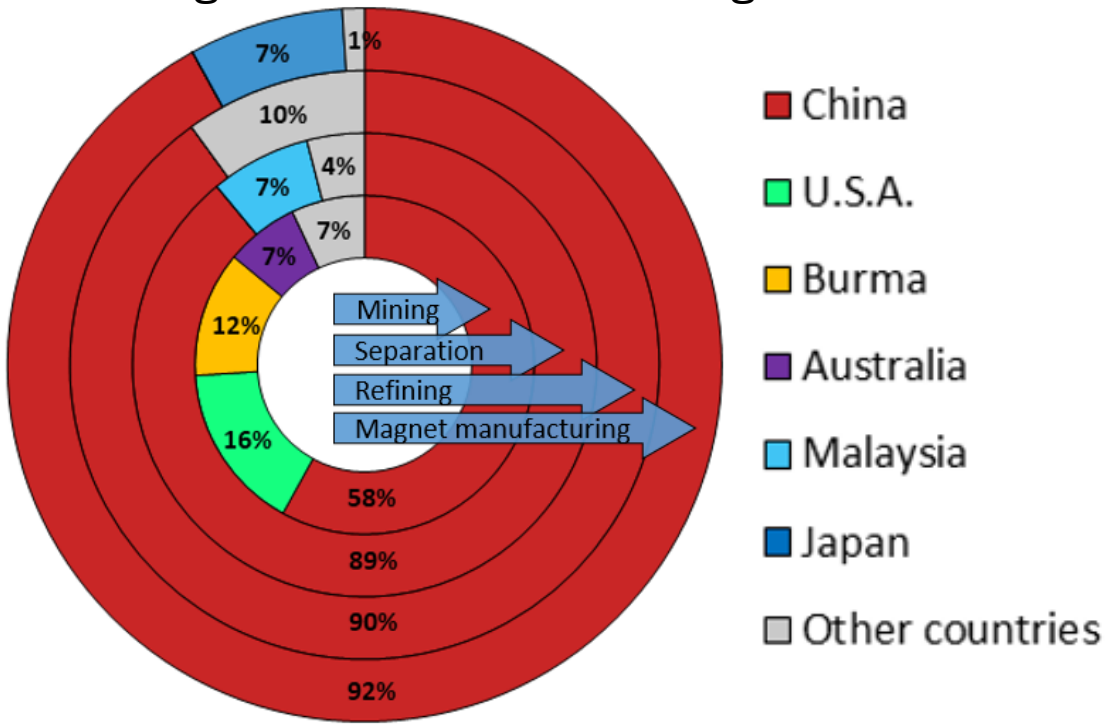
Semiconductors, Electronics, and Other Technologies Manufacturing

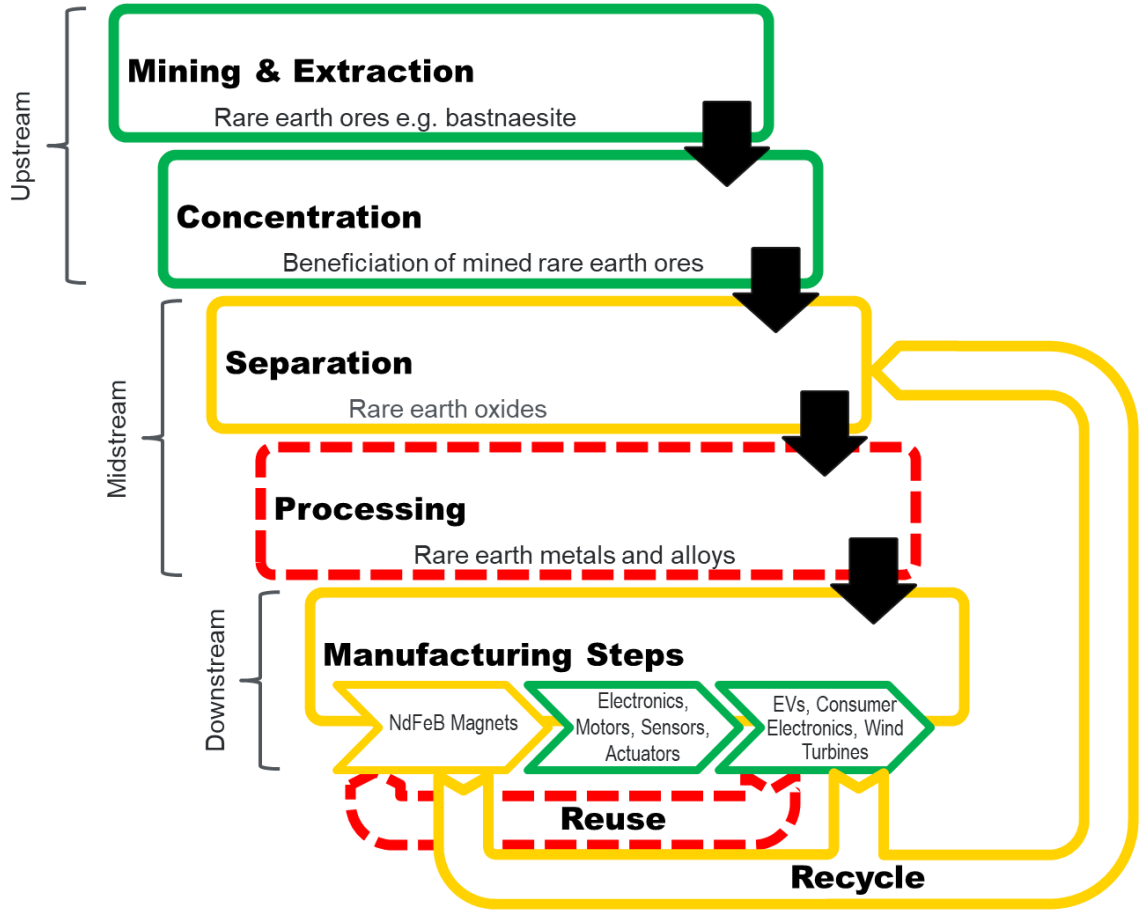
Entrepreneurial Ecosystems and Advanced Mfg. Workforce

Supply Chain Vulnerabilities

- Up-to-mid stream capabilities **are geographically concentrated**
- **Lack of midstream capabilities are a gap** that limit growth of upstream supply and downstream value-add manufacturing

Geographic concentration of supply chain stages for sintered NdFeB magnets





https://www.energy.gov/policy/securing-americas-clean-energy-supply-chain

Critical Minerals & Materials (CMM) RD&D in AMMTO

Points of Contact:
CMI, Analysis, Interagency: helena.khazdozian@ee.doe.gov
Lithium Center, Circular Economy, Workforce: jeremy.mehta@ee.doe.gov

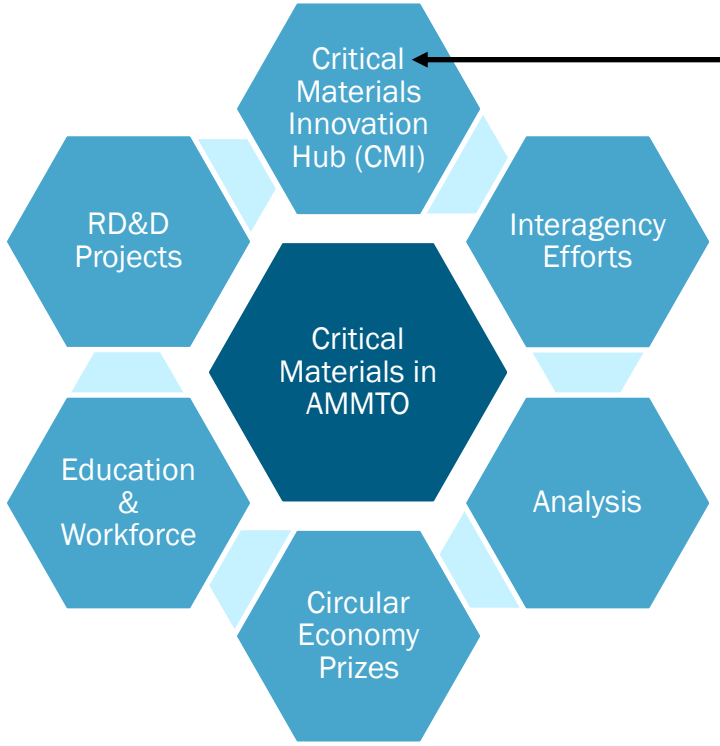
AMMTO's CMM portfolio addresses high-impact opportunities and challenges across the entire life cycle of high priority CMM for energy technologies

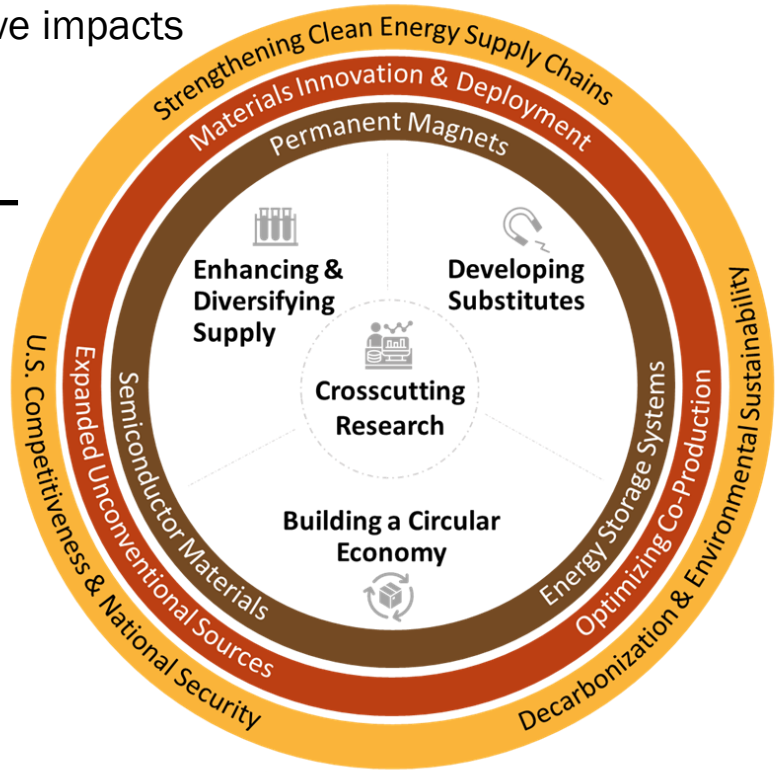
- **Research, development, and demonstration (RD&D) for high-priority critical minerals and materials, aligned with the DOE Critical Minerals and Materials Strategy, to:**
  - Build resilient domestic supply chains to support the clean energy transition
  - Accelerate adoption of innovative S&T solutions to improve efficiency and reduce negative impacts
  - Foster a robust innovation ecosystem to meet industry and research workforce needs

RD&D Projects

- R&D to advance next-generation technologies, in coordination with the CMI
- Lithium RD&D Virtual Center to integrate and expand the innovation ecosystem
- Demonstrate improved industrial technologies to address supply chain gaps
- De-risk and validation of innovation through the Critical Materials Accelerator Program

Critical Materials Assessment





CMI Critical Materials Innovation Hub

Critical Materials Innovation Hub (CMI)

formerly known as the Critical Materials Institute

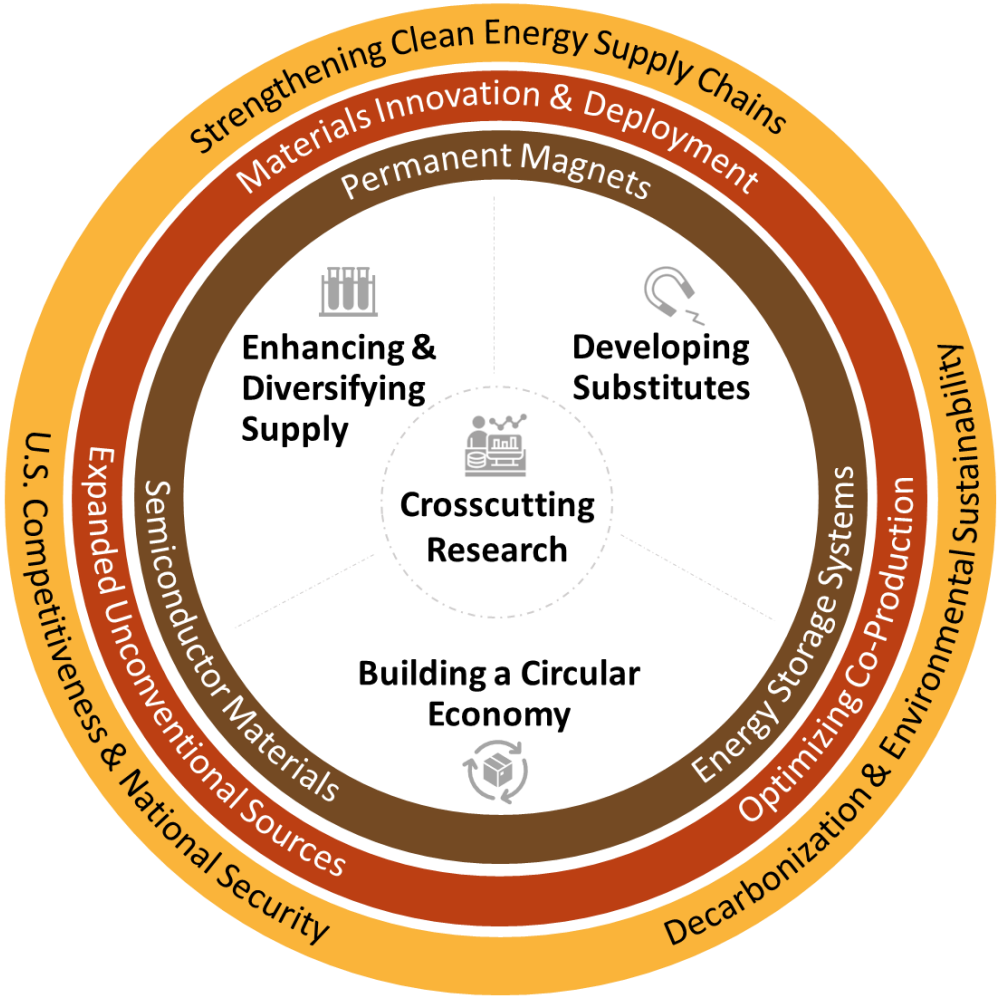
Focused on advancing cost-effective extraction, separation, processing, metallization, substitution, and recycling of critical materials, to support U.S.-based supply chains for high-value add technologies that rely on these materials (permanent magnets, energy storage, electronics).

People: 250+ strong, bolstered by education and workforce development

Innovative Ecosystem: network of 45+ active team members across critical material supply chains

Portfolio: 32 early-stage research projects building on 10 years of research resulting in 500+ publications, 12 R&D100 Awards, 50 patents, and licensed 20 technologies to industry

CMI | Critical Materials Innovation Hub



CMI Facilities & Capabilities

FACILITIES

High-throughput centrifugal contactor system

Solvent extraction test bed facilities

Multi-stage solvent extraction lab scale mixer-settler demo test facility

Materials Preparation Facility

Magnet Scale-up and Prototyping Facility (MSPF)

Controlled Atmospheric Magnet Processing (CAMPS)

CAPABILITIES

Mining & Concentration | Extraction | Separation | Conversion to Metals | Refining & Alloying | Recycling | Fabrication | Part Manufacturing | Sub-Assembly Manufacturing | System Integration

Bench-scale metal reduction
Electrophoretic deposition

Thermal processing in high magnetic fields
Robotic magnetic property assessment
Table-top 3D magnet printing

Crosscutting Enabling Facilities & Capabilities

- Bulk and thin-film combinatoric library production facilities
- Rapid thermodynamic property assessment
- Micro-x-ray fluorescence analysis
- High precision adiabatic calorimeter
- Automated machine learning-assisted X-ray imaging defect detection
- Computational prediction and automated synthesis of molecules/ligands using AI/machine learning-augmented robotic systems to rapidly screen and identity new ligands
- Criticality assessment tools & techniques
- Open-source software to evaluate techno-economic analysis and life-cycle assessment
- Roadmapping

CMI Innovations – Magnet Supply Chain

Critical Materials Innovation Hub

[Learn More: CMI Technologies with Magnets]

Mining & Concentration → Extraction → Separation → Conversion to Metals → Refining & Alloying → Recycling → Fabrication → Part Manufacturing → Sub-Assembly Manufacturing → System Integration

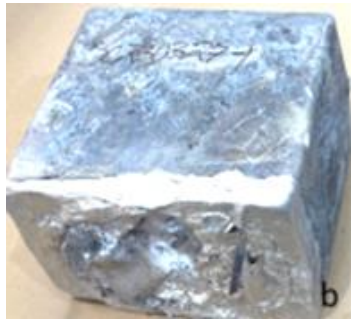
Efficient Flotation

One-step HCl Leaching

Membrane Solvent Extraction

Novel Ligands for Improved Oxide Separation

Low Temperature Metallization



Critical REE-Lean Magnets

Cast Critical REE-Free Gap Magnets

Electrochemical, Acid-free, Bio-based, & Automated Recycling Technologies

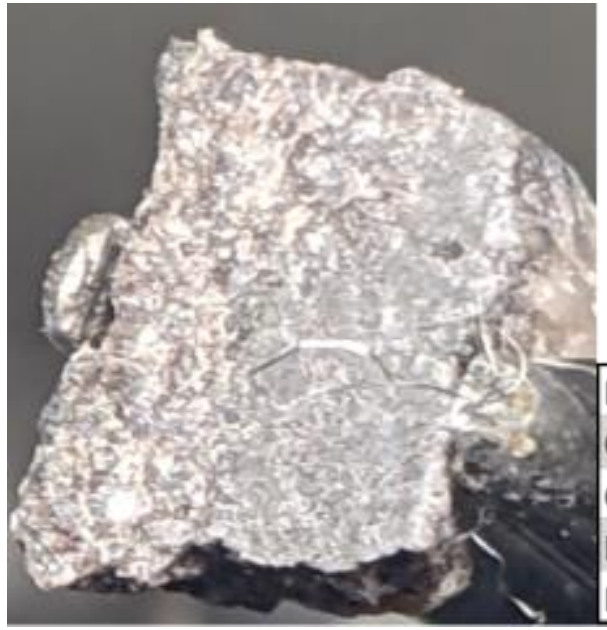
Hot-roll Dy-free Nanograin Neo Magnet

Additively Manufactured Bonded Magnets

Improvements to Metallization

- Proprietary dimensionally-stable anode enables stable, energy-efficient Nd electrolysis from chloride melts
- Eliminates CO2 and PFC emissions

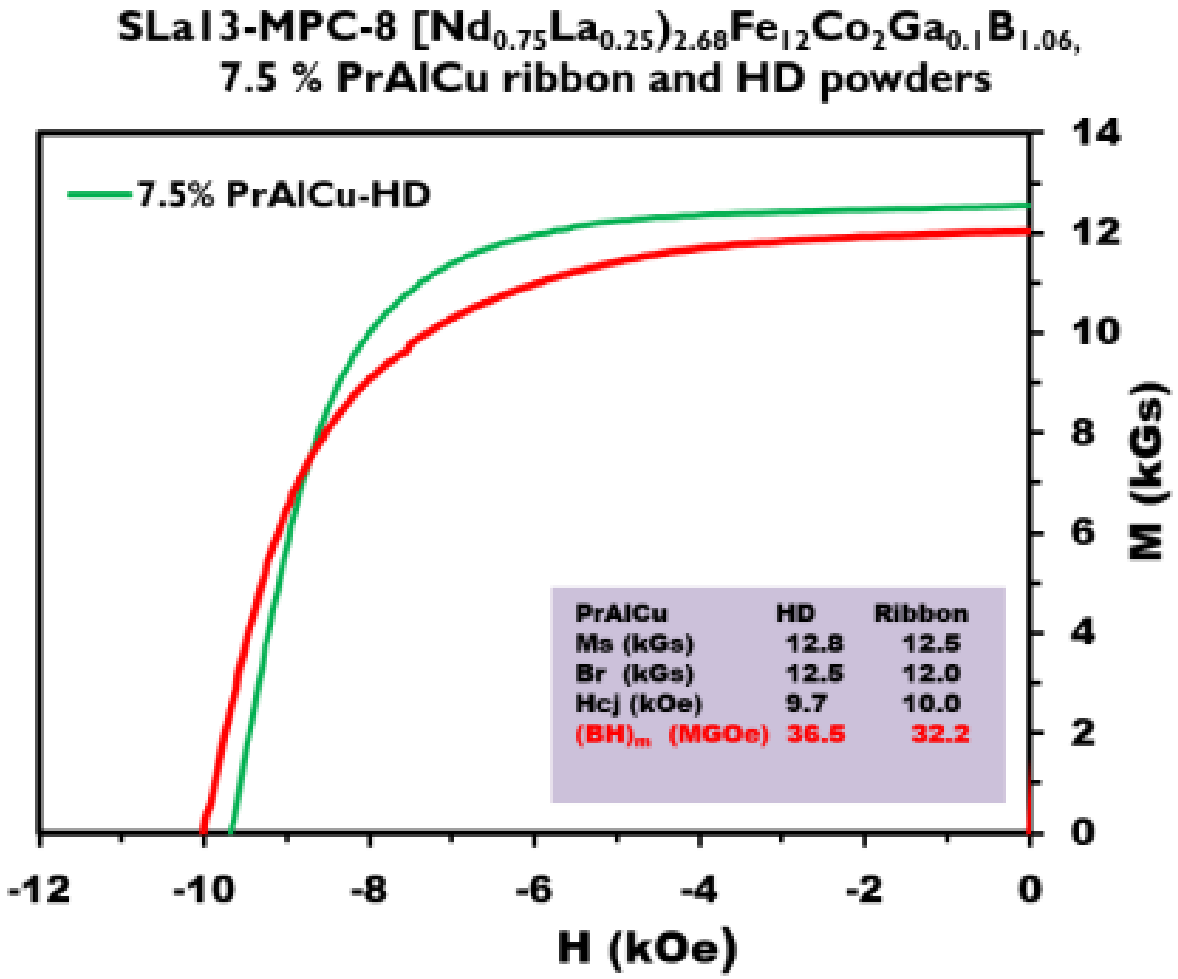
- Low temperature, semi-continuous reduction from Nd salts



Element	Net Counts	Weight %	Atom %
O (k)	2368	0.31	2.59
Cl (k)	20464	1.43	5.4
K (K)	3865	0.27	0.94
Nd (L)	672483	97.99	91.07

Reducing Critical REEs

- Created a category of Nd-lean mid-grade magnets, with up to 50% of the Nd replaced with mischmetal while maintaining the (BH)max at 32.6 MGOe.
- Maximized the benefit of using Nd in 2-14-1 based magnets with (BH)max between 30-35 MGOe.
- Grain boundary engineering is proven to be effective for enhancing coercivity. Future research will focus on this direction.

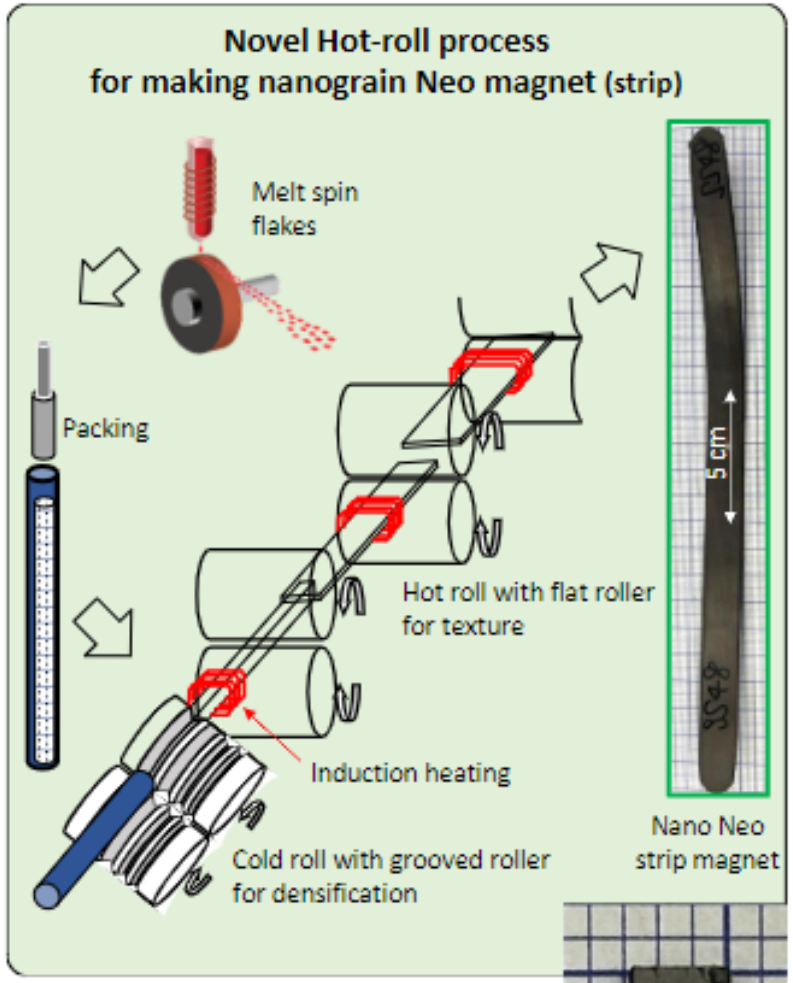


Manufacturing Advances – Hot Rolling

- **Cost-effective and semi-continuous manufacturing process for making Nd-Fe-B nanograin magnets**
  - Reduction of complexity using a deformable die concept
- **Functionality at high temperature without Dy**

2023 R&D 100 WINNER

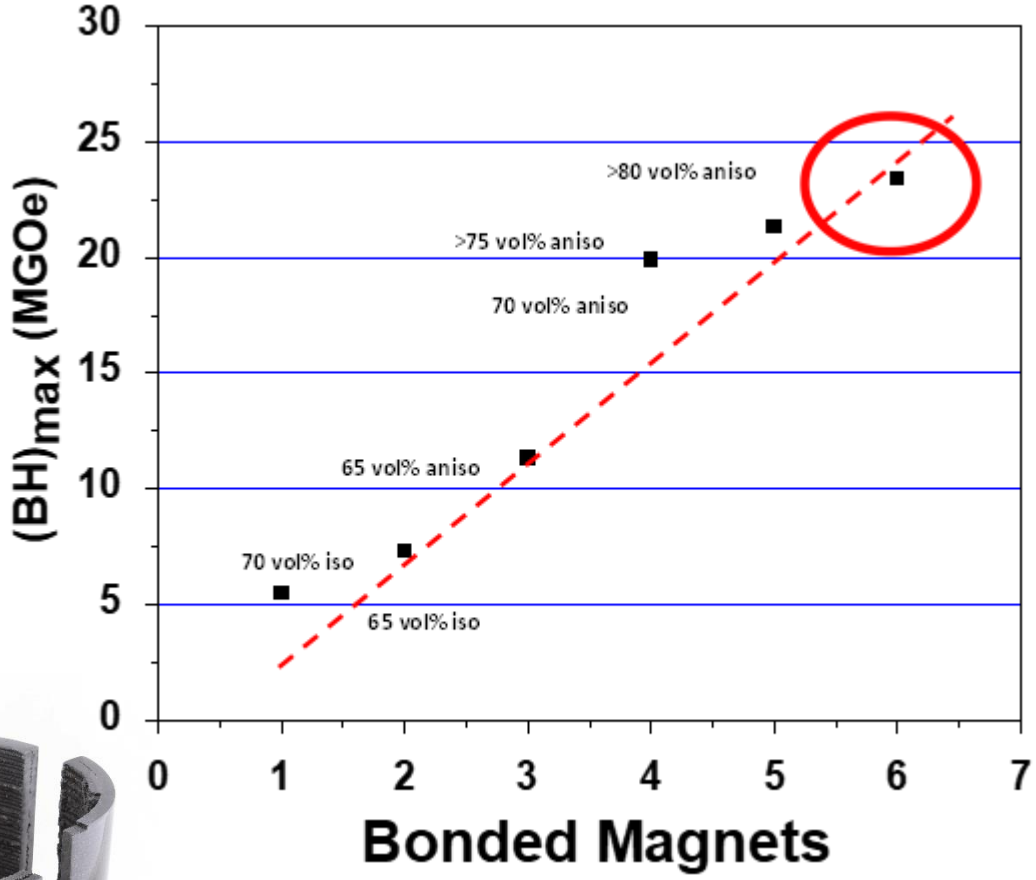
2023 R&D 100 BRONZE



H_{cj} (kOe)	13.0
M_r (kG)	13.0
$(BH)_{max}$ (MGOe)	37.6

Manufacturing Advances – Additive Manufacturing

- Successfully printed bonded magnets using anisotropic NdFeB magnet particles up to 70 vol% with epoxy polymer binders
- Additively printed magnets result in high energy product of up to 24 MGOe and outperformed conventional injection molded and compression molded magnets
- Potential to increase profit by 9.07% and lower global warming potential by up to 30% compared to injection molding

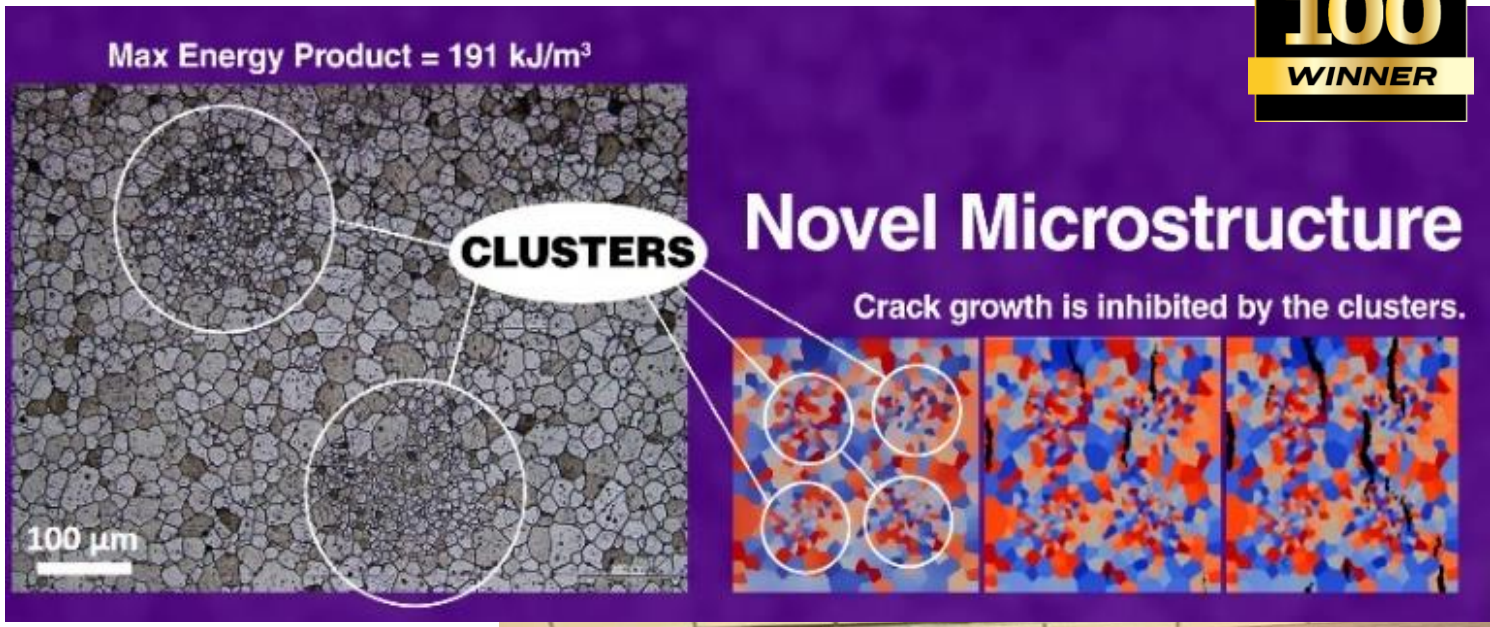


2017 R&D 100 WINNER

TechConnect INNOVATION AWARD 2019

Manufacturing Advances – Tough SmCo

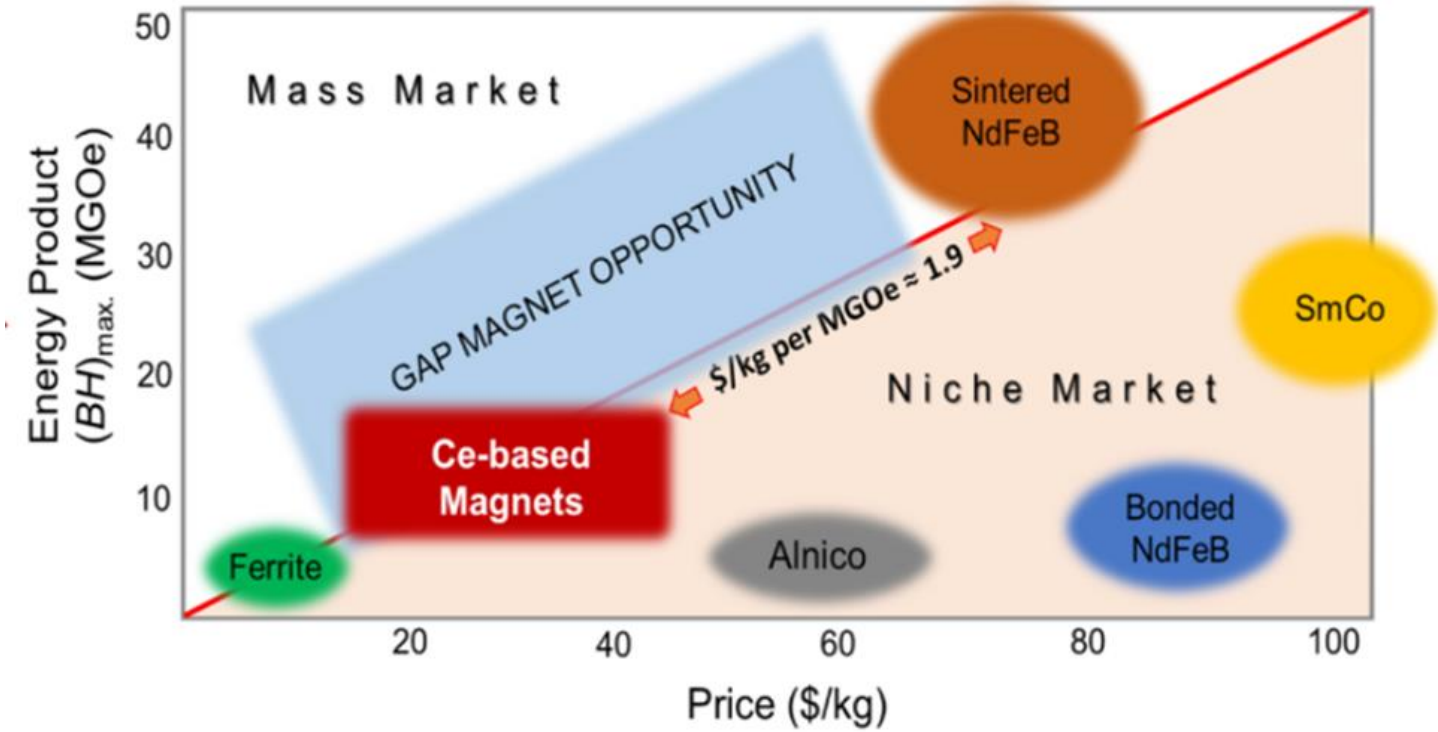
- Novel mechanically robust SmCo magnets via Sm_2O_3 particulate-modified grain-refined microstructure engineering
- Flexural strength was increased by 50% Magnet machining waste ratio reduced by ~15%
- Demonstrated cost-effective, scalable, and industry compatible powder synthesis routes (low-energy ball milling)



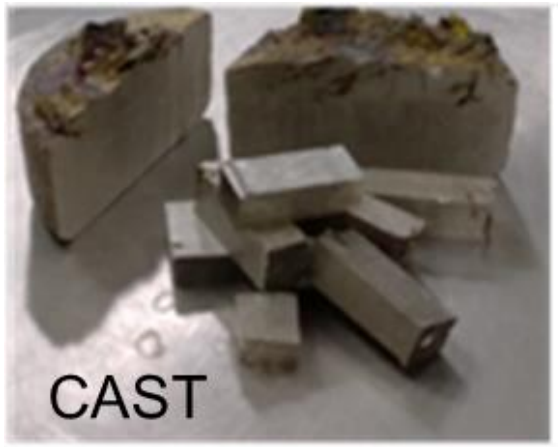
Industry-scale Sm_2O_3-modified $Sm_2(Co,Fe,Cu,Zr)_{17}$ sintered magnet cube blocks

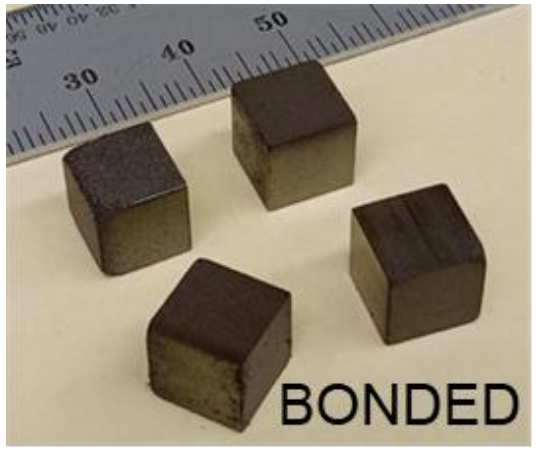
"Gap" Magnets – Addressing the REE Balance Problem

- One-step cast cerium-based "gap" magnet ingot
- 4 MGOe bonded magnet with 50% better remanence than bonded ferrite magnets



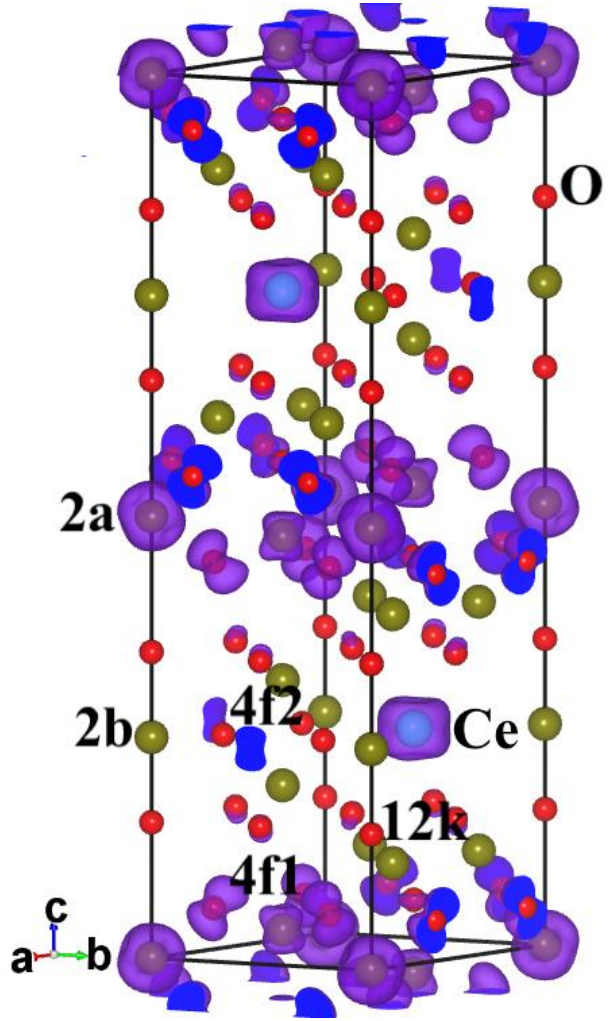
2023 R&D 100 WINNER





“Gap” Magnets – Ce-Substituted Hexaferrite

- Theoretical calculations determined a giant magnetocrystalline anisotropy in Cerium substituted M-type hexaferrite.
- Ce increases the magnetocrystalline anisotropy constant of the parent compound by at least an order of magnitude. The net magnetic moment also increases as the anisotropy-producing Cerium *4f* electrons also create an orbital moment.
- Potential for a new critical-element-free permanent magnet material adopted for use in devices such as automotive traction drive motors.



Electron charge density contour occupying the valence bands near the Fermi level

C. Bhandari and D. Paudyal, *Phys. Rev. Applied* **20**, 024016 (2023).

Building a Circular Economy – Pilot Development

CMI Critical Materials Innovation Hub

Acid-free dissolution recycling

- Eliminates operational hazards and negative environmental impacts
- >99.5% pure NdPr and Dy oxide from e-waste (8000 kg batch size)
- Modular scale-up

2018 R&D 100 WINNER

TechConnect INNOVATION AWARD 2019

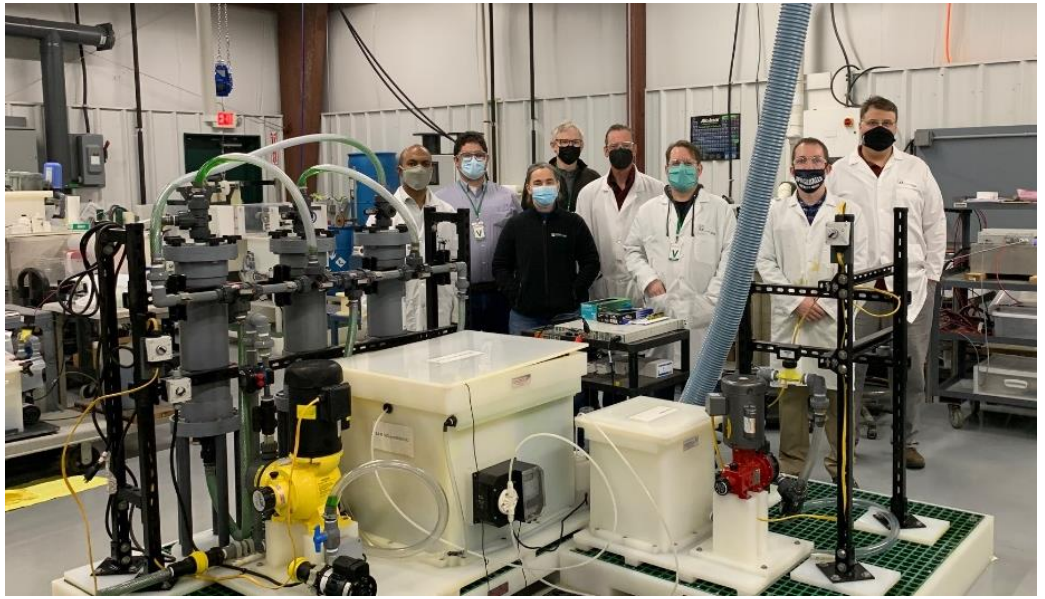
Shredded HDDs prior to recycling

Shredded HDDs after REEs leaching

Sample of recovered rare earth oxide

Electrochemical Recovery (E-RECOV)

- Low temperature recovery of PGMs and REEs from e-waste
- No solvents used
- Co-recovery of Ag, Au, steel

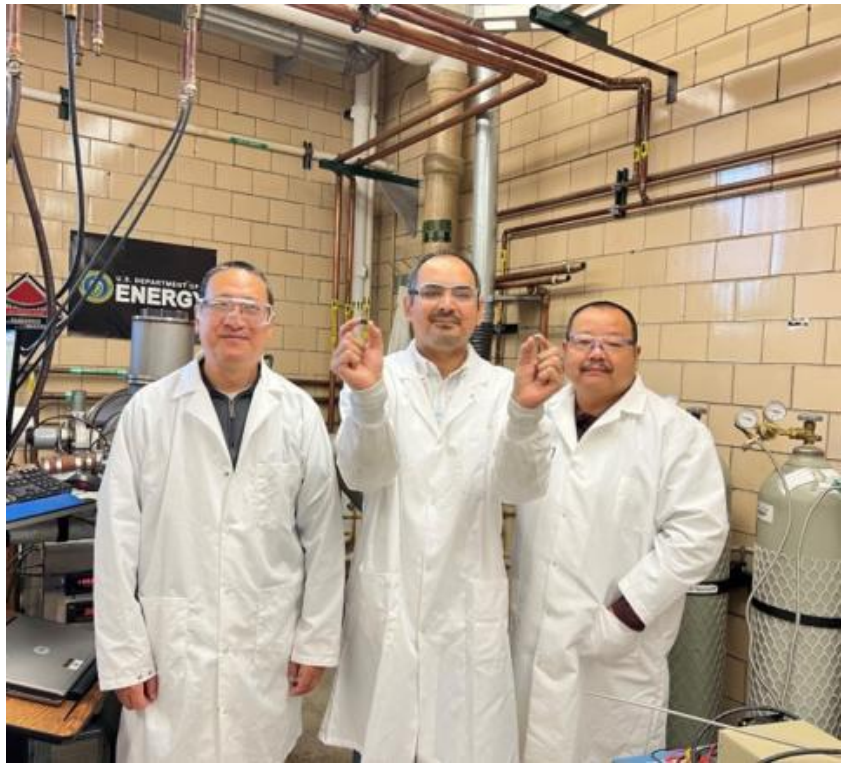


Education & Workforce Development Highlights

CMI Critical Materials Innovation Hub

Magnet Short Course held in 2023 | CMI Lesson Plans

CMI postdoc, Dr. Kinjal Gandha, transitioned to MP Materials as a Magnetics Engineer



Advanced Magnet Lab (AML) employee, Dr. Rakesh Chaudhary, trained on permanent magnet fabrication and innovation at Ames National Laboratory

Critical Materials Collaborative

CRITICAL MATERIALS COLLABORATIVE
U.S. DEPARTMENT OF ENERGY

The CMC is the **connective tissue** within the DOE Critical Materials Program and the U.S. government, aligning our research portfolio with DOE climate goals and accelerating RD&D adoption.

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

From Basic Science to Commercialization

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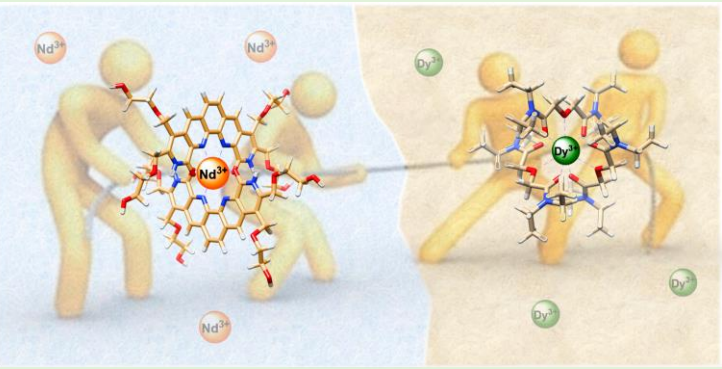
Commercialization of highly selective processes is underpinned by basic science discovery

Basic Science

New strategies for separation of rare earth elements discovered through computation modeling and X-ray adsorption spectroscopy.



Applied R&D

Novel ligands/extractants were designed that show improved separation of rare earth elements.

These outperform the industry standard with implications to reduce cost and footprint of the separation process.

Technology Commercialization

CMI industry partner Marshallton Research Laboratories licensed the technology and is working to commercialize the production of the novel ligands to meet the needs from a variety of companies.

"We're working with several companies while also improving and scaling up manufacturing processes," Foster explains.

Unprecedented Federal Investment in Critical Materials

U.S. DEPARTMENT OF ENERGY

- **~$211 million in Fiscal Year 2023** enacted on critical minerals and materials
- **Bipartisan Infrastructure Law (BIL) provided over $8 billion** in funding dedicated to critical minerals and materials advancement, such as:

Battery Materials, Manufacturing and Recycling Demos and Commercialization
$6 billion

Rare Earth Elements Demonstration Facility
$140 million

Critical Materials RDD&D Program
$600 million

Critical Material Supply Chain Research Facility
$75 million

Clean Hydrogen Electrolysis Program
$1 billion

Unprecedented Federal Investment in Critical Materials

Recent funding opportunities, selections, and awards include:

$2.8 billion for **battery materials processing** and battery **manufacturing recycling**

$74 million to advance domestic **battery recycling and reuse**

$107 million to **expand critical materials production capacity for lithium-ion batteries**

$350 million for **long-duration energy storage** demonstration

$30 million lab call for **long-duration energy storage**

$16 million for front-end engineering design studies for the **REE demonstration facility.**

$12 million for **lithium extraction and conversion from geothermal brines**

$39 million for the Mining Innovations for Negative Emissions Resource Recovery **MINER program**

$17.5 million to **commercialize critical material-free permanent magnets** through the SCALEUP program

Funding Opportunities

Bipartisan Infrastructure Law (BIL) 40207(b) Battery Materials Processing & BIL 40207(c) Battery Manufacturing Grants Round II

- Funding Opportunities: $3.5 billion
- Office of Manufacturing & Energy Supply Chain

Critical Materials Accelerator Program

- Funding Opportunity: $10 million
- Advanced Materials & Manufacturing Technologies Office

Critical Material Innovation, Efficiency, and Alternatives

- Funding Opportunity: $150 million
- Office of Fossil Energy & Carbon Management

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Learn more: energy.gov/criticalmaterials

Inflation Reduction Act (IRA) – Energizing the Private Sector

- 30D Clean Vehicle Credit has critical mineral sourcing and recycling requirements
- 45X Advanced Manufacturing Production Credit has 10% production cost credit for critical mineral and electrode active material production
- 48C Advanced Energy Project Credit has investment tax credit for critical material processing, refining, or recycling
- 50141 Funding allows DOE to provide loans for critical minerals processing, manufacturing, and recycling

Battery Supply Chain Investments post-Inflation Reduction Act
https://www.energy.gov/invest

Stay Connected

Learn more about DOE's Critical Materials Program
energy.gov/cmm/critical-minerals-materials-program

Connect the CMC
energy.gov/cmm/critical-materials-collaborative
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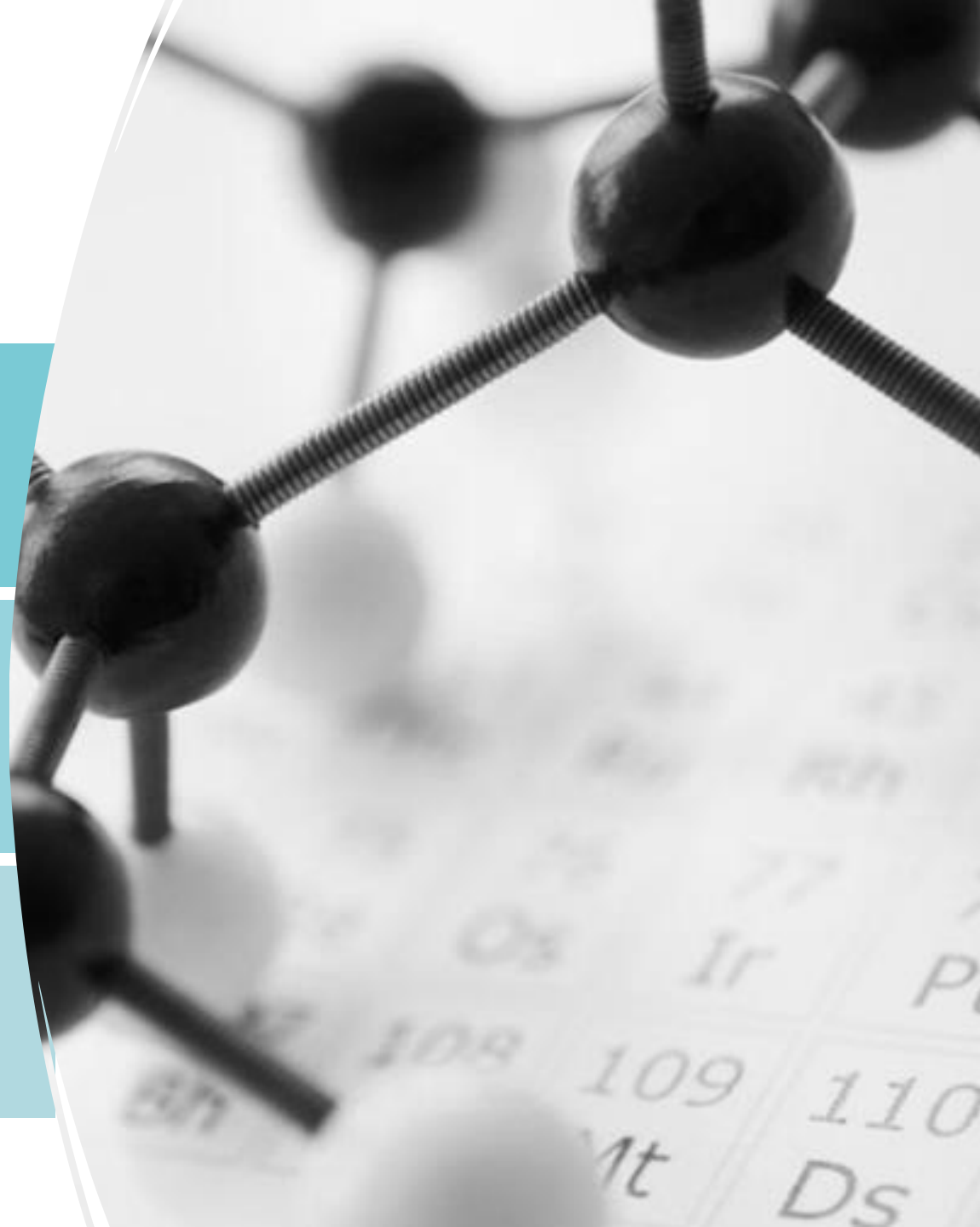
Connect with CMI
https://www.ameslab.gov/cmi
Partner Relations: sjoiner@ameslab.gov



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