

2021 Virtual Annual Technical Review Meeting

Current Uses and Future Opportunities for U.S. Industry in Rare Earth Elements and Critical Materials Technologies and Markets: Knowledge-Base Tool Development (05-PSU-V1-04: Rare Earth Elements)

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**U.S. DEPARTMENT OF
ENERGY**



University Coalition for Fossil Energy Research

Earth and Mineral Sciences
Energy Institute



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and Mineral Sciences

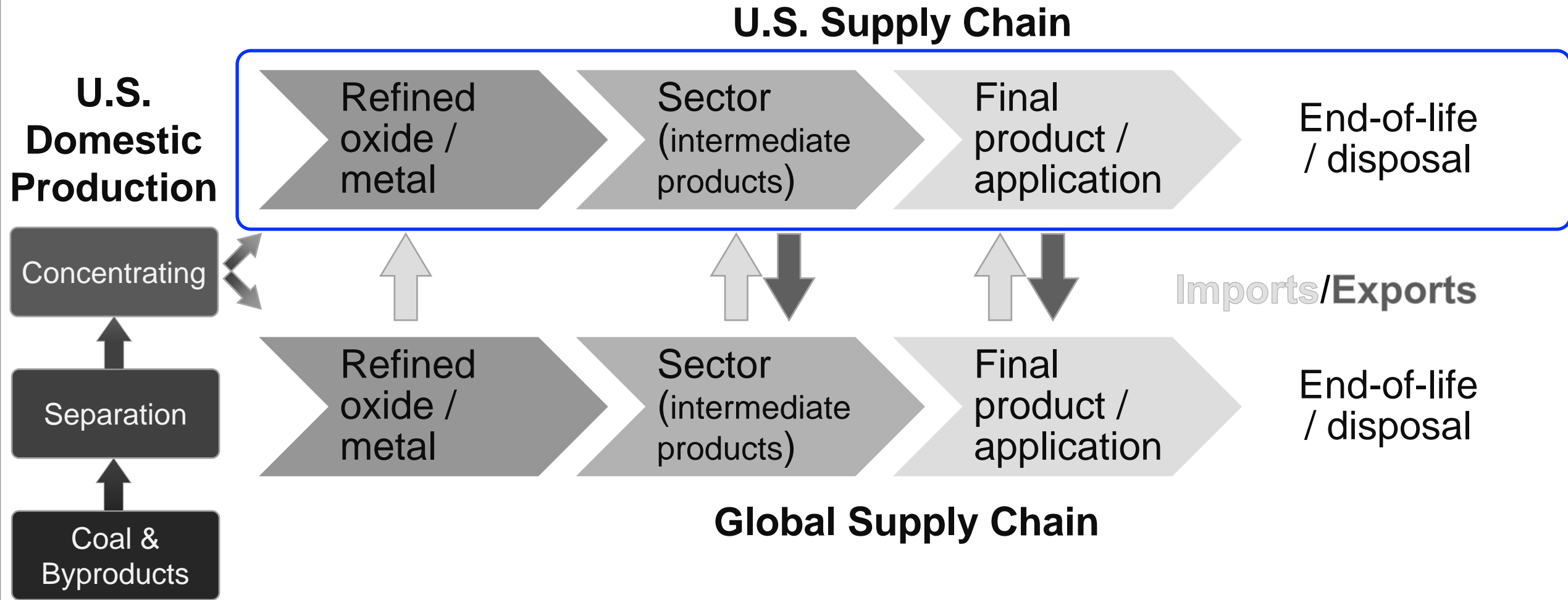
Organization

- Guiding directives
- Project overview & General workflow
- Introduction: Rare earth \neq rare in the earth
- Project tasks
- Additional supporting activities

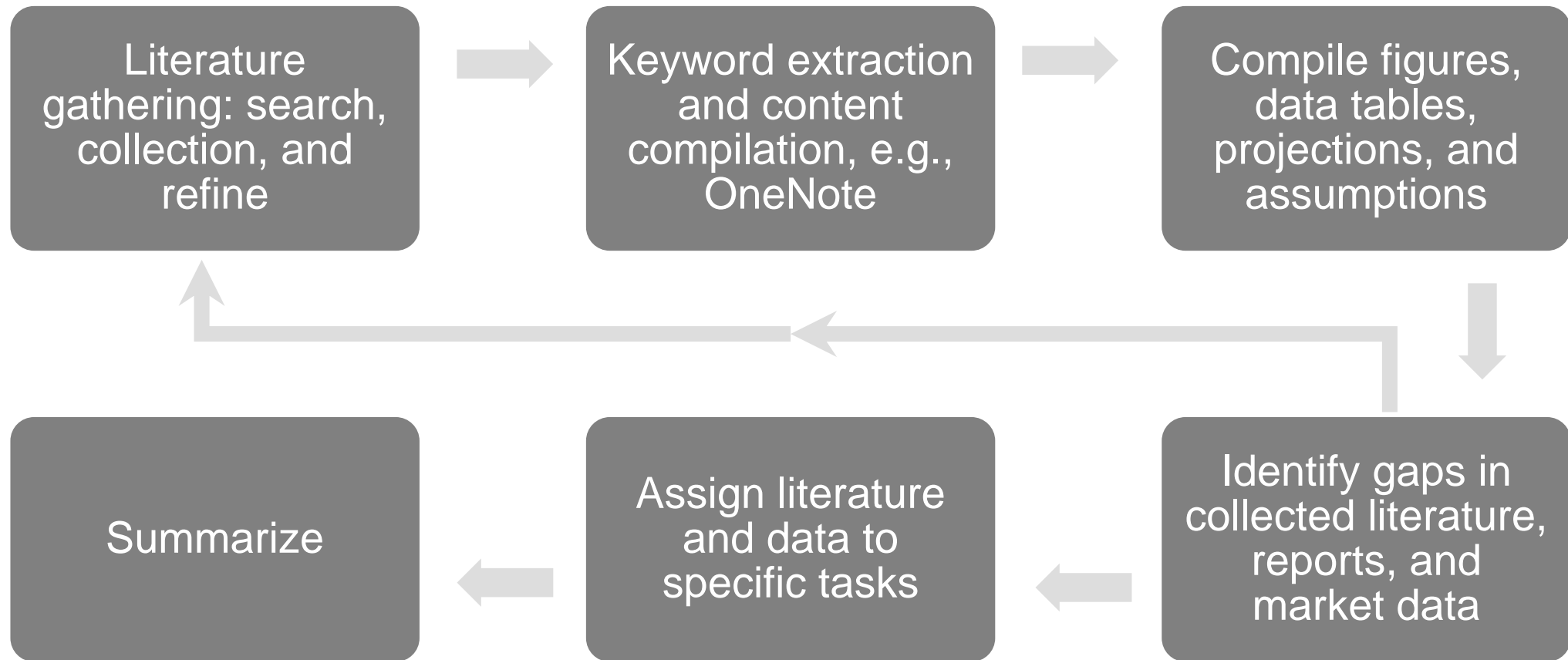
Directives

- Guided by Executive Orders 13953 and 14017
 - Bolster resilience of U.S. supply chains and strengthen production of critically important domestic resources
- Aligns with DOE-NETL near-term goals
 - Validate technical and economic feasibility for production of high-purity (90-99%), salable rare earth compounds from coal and coal byproducts

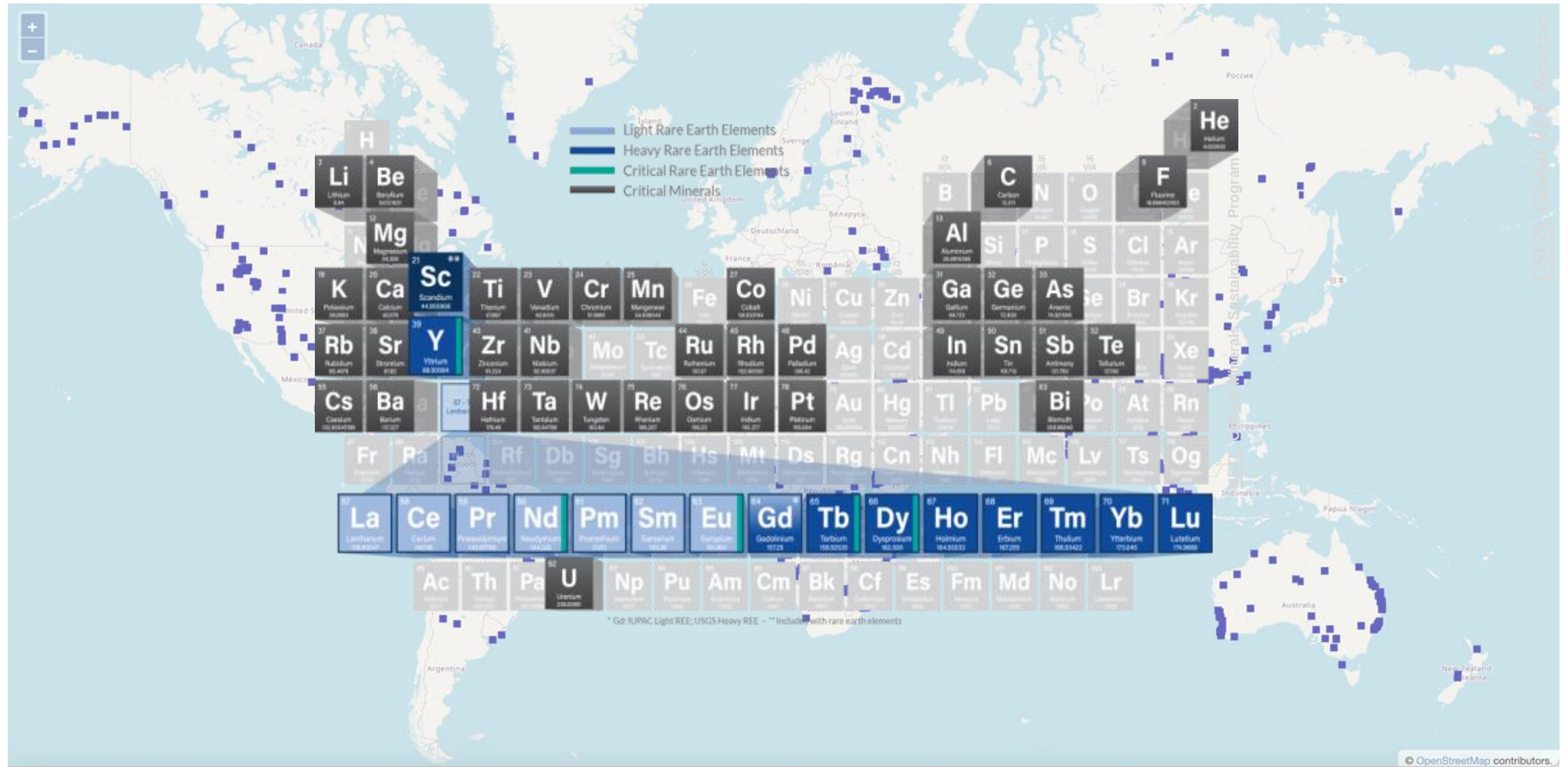
Project overview



General workflow process



Introduction: Rare earth \neq rare in the earth



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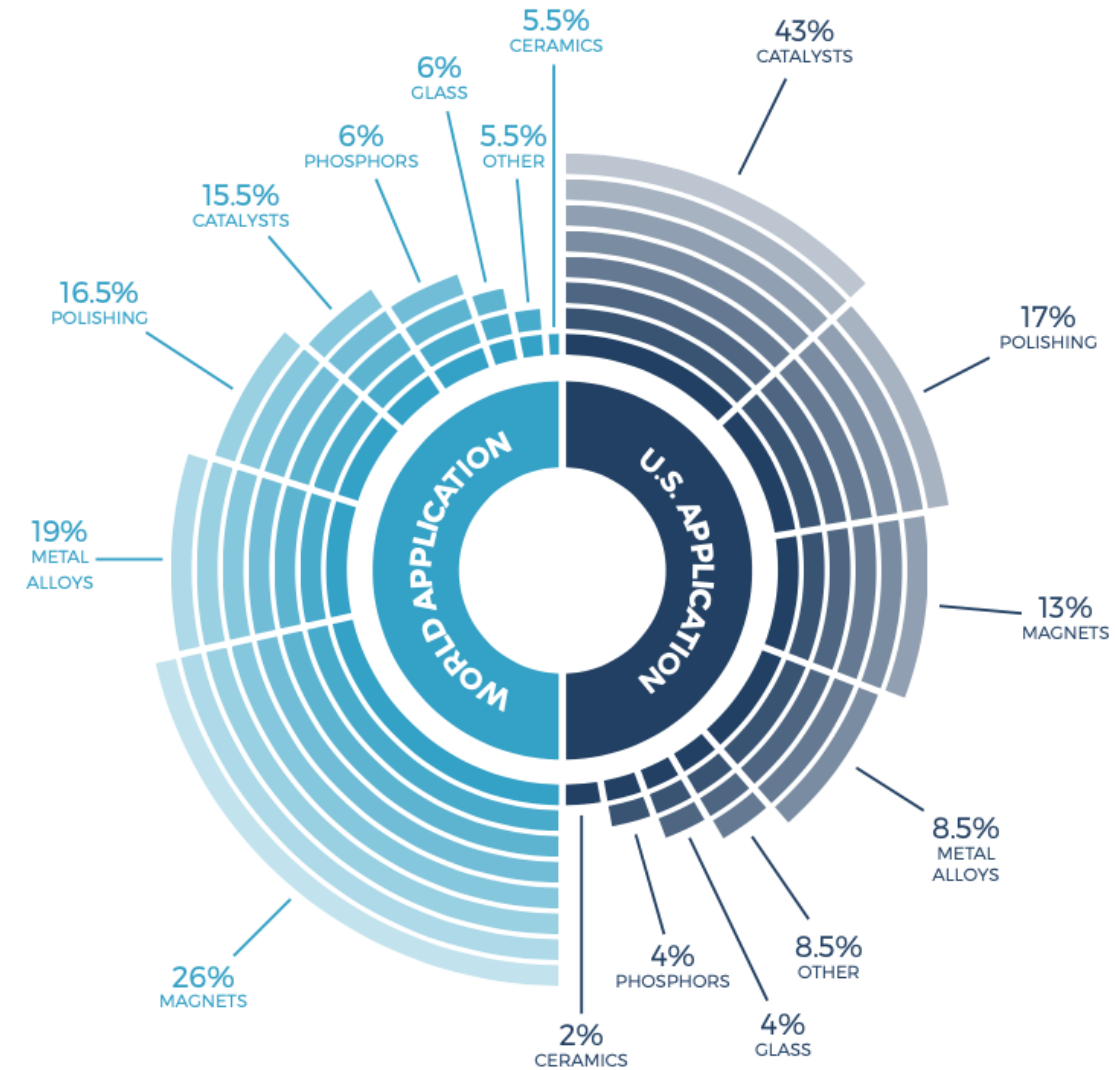
Project tasks: Task 1

Identify the industrial opportunity for utilization of REE and REE-containing materials within the U.S. if a domestic supply of high purity REEs were to be available, and where could it be utilized to ensure that the REEs remain within the U.S.

- Prior work
 - 59% REE use in mature markets (catalysts, glassmaking, lighting, metallurgy)
 - 41% REE use in high-growth markets (battery alloys, ceramics, permanent magnets, energy, and lasers)
- Prioritized REEs & CMs in electrification (high-growth demand market)
 - Lithium and graphite used in batteries
 - Nd, Dy, Y, Pr, Sm, Eu, and Tb used in permanent magnets and renewable energy tech
 - Other REEs and CMs addressed with second phase
- Q3 work to address REEs & CMs in long-term, future demand markets
 - TBD

Uses: Industrial applications, World and U.S.

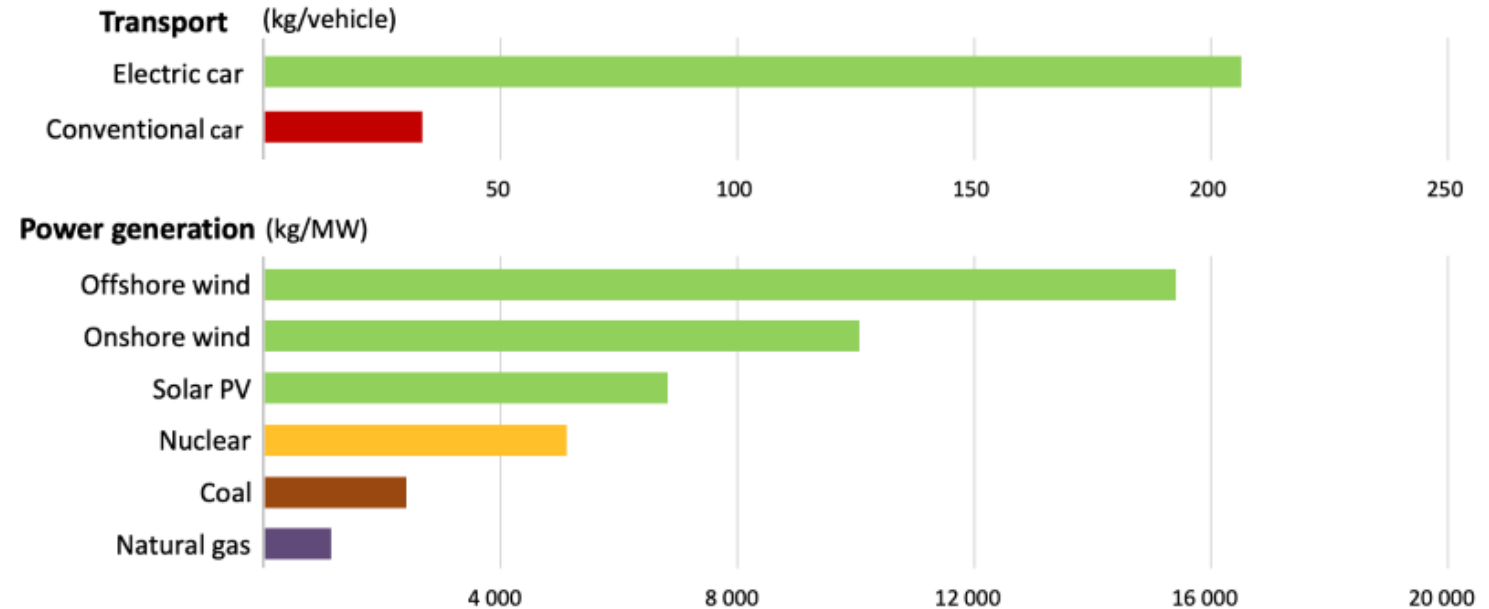
- Mature markets consume upwards of 60% domestic, 50% global REEs
 - La and Ce constitute ~80%
- Newer, high-growth markets (e.g., battery alloys, ceramics, and permanent magnets) drive the remaining
 - Dy, Nd, and Pr constitute ~85%



Demand drivers: Electrified

- Increasing electrification shifts consumption to a more mineral-intensive system

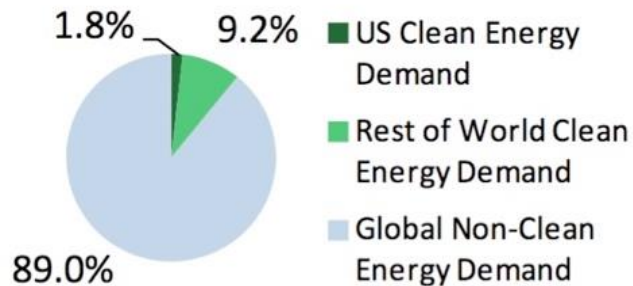
Minerals used in selected energy technologies



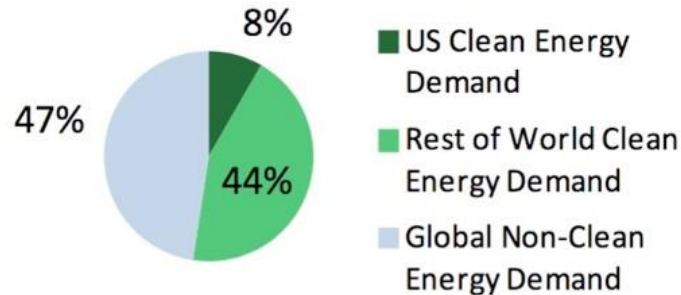
IEA, The Role of Critical World Energy Outlook Special Report Minerals in Clean Energy Transitions

U.S. DOE, Report on Critical Materials Strategy

2010

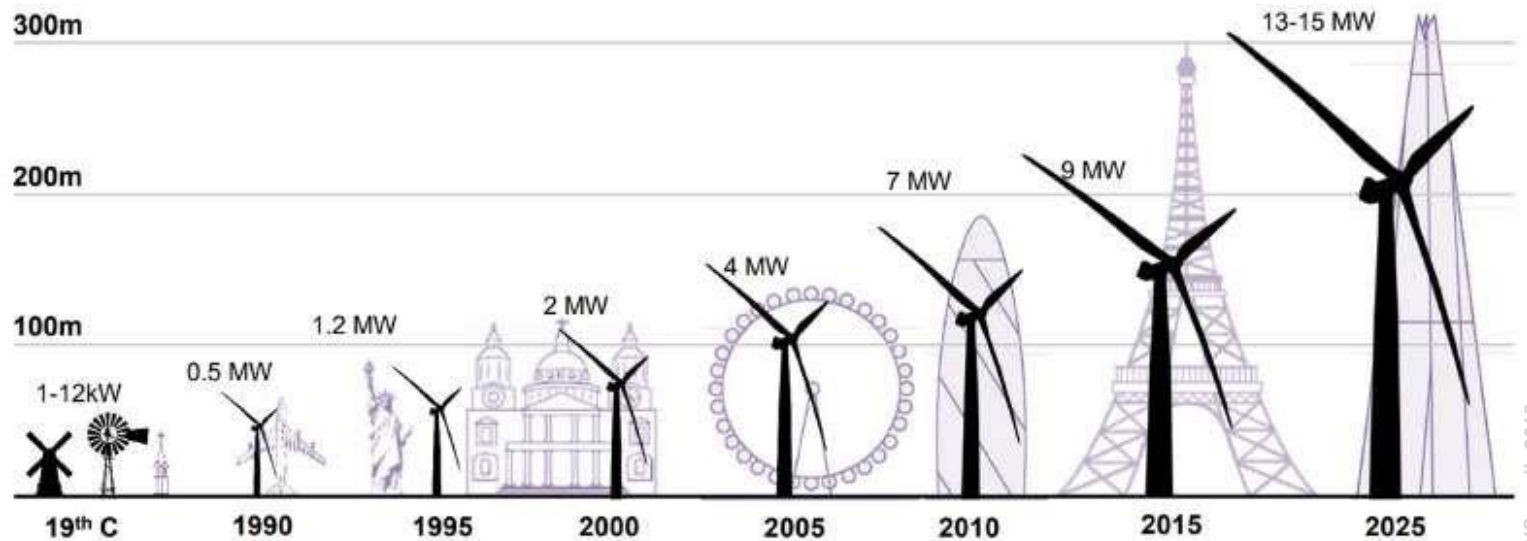


2025

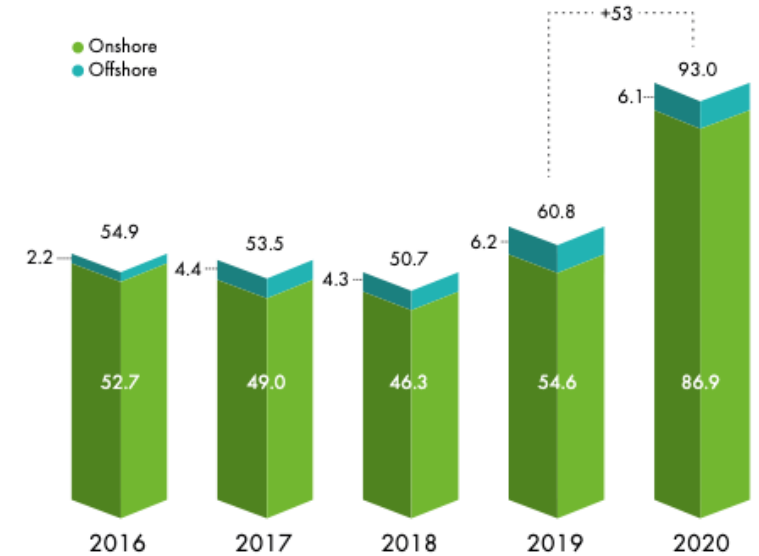


Clean energy - wind fuels REE consumption

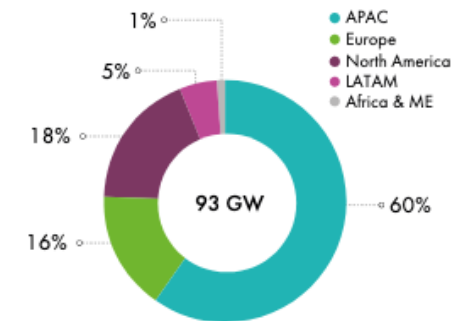
- Permanent magnets in generators
 - REE demand increasing (Pr, Nd, Tb, Dy) with larger wind turbines
 - 2030 projections anticipate a 2.5-5x increase in REE consumption over 2020



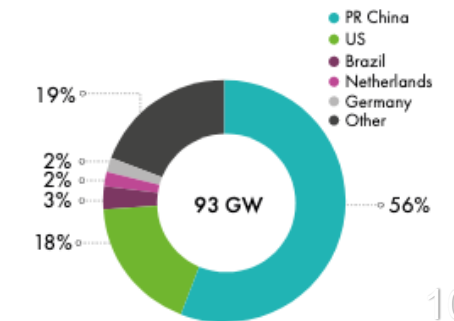
New installations



New wind power capacity in 2020 by region Per cent

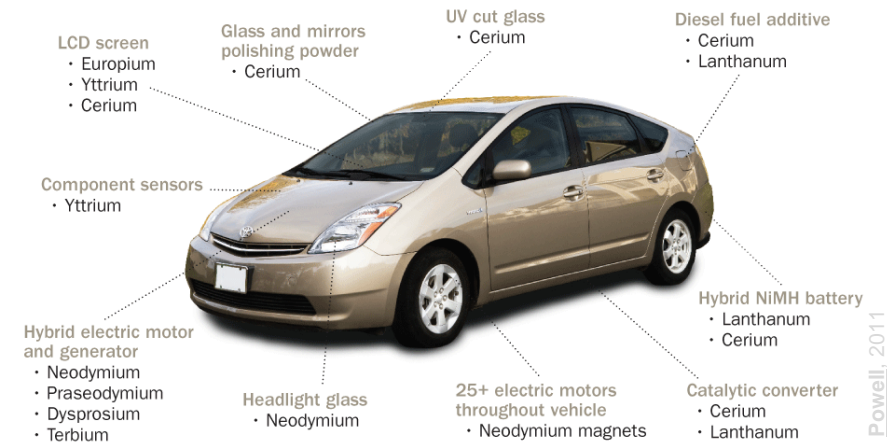
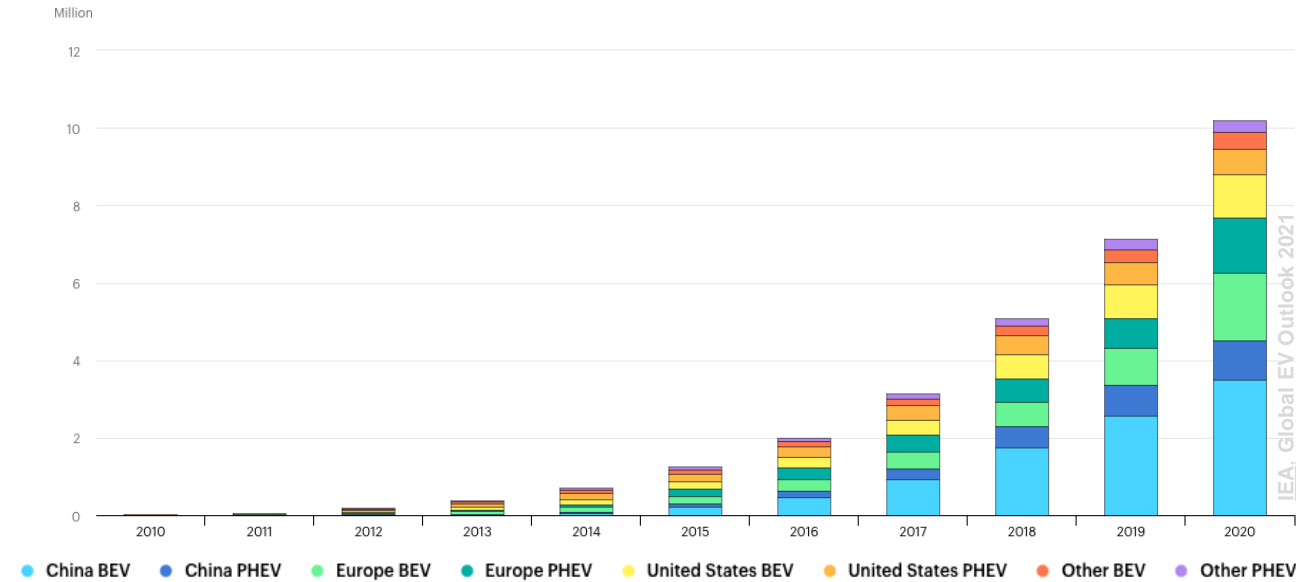


New wind power capacity in 2020 and share of top five markets Per cent



Electric vehicle consumption driving REE use

- Increased consumption of BEVs and PHEVs
 - Trend continues in U.S.
 - Governments, manufacturers, and companies committed to electrified transportation
- REEs in automobiles
 - ~500g in ICE autos (mostly NdFeB magnets)
 - ~5,200g in Hybrid autos (>90% Nd)



Project tasks: Task 2

Identify current industries and specific companies that utilize rare earths within the U.S. Determine what volume of REEs would be necessary to supply these facilities and where these supply opportunities are located.

- Global REE consumption growth rate of >10% annually
- Few major U.S. manufacturers identified
 - Manufacturing production data sought, Q3 estimated
 - Broader domestic network to be developed

**GLOBAL MARKET FOR RARE EARTHS, THROUGH 2016
(METRIC TONS — REO EQUIVALENT)**

Industry	2009	2010	2011	2016	CAGR% 2011-2016
Mechanical/metallurgical	34,355	44,830	50,880	76,965	8.6
Glass and ceramics	28,680	36,310	39,500	60,000	8.7
Chemical	20,250	22,835	24,785	32,600	5.6
Energy	17,374	23,070	27,327	61,972	17.8
Electronics, optics and optoelectronics	7,240	10,450	11,840	21,270	12.4
Others	3,667	3,773	3,897	5,177	5.8
Total	111,566	141,268	158,229	257,984	10.3

Project Tasks: Task 3

Provide an overview of global CM resources, resource location, and **processing** of resource materials leading to the production of all 37 CMs.

- Current work is evaluating
 - USGS Mineral Commodity Summaries
 - Market analysis reports
 - Global Input/Output Economic models

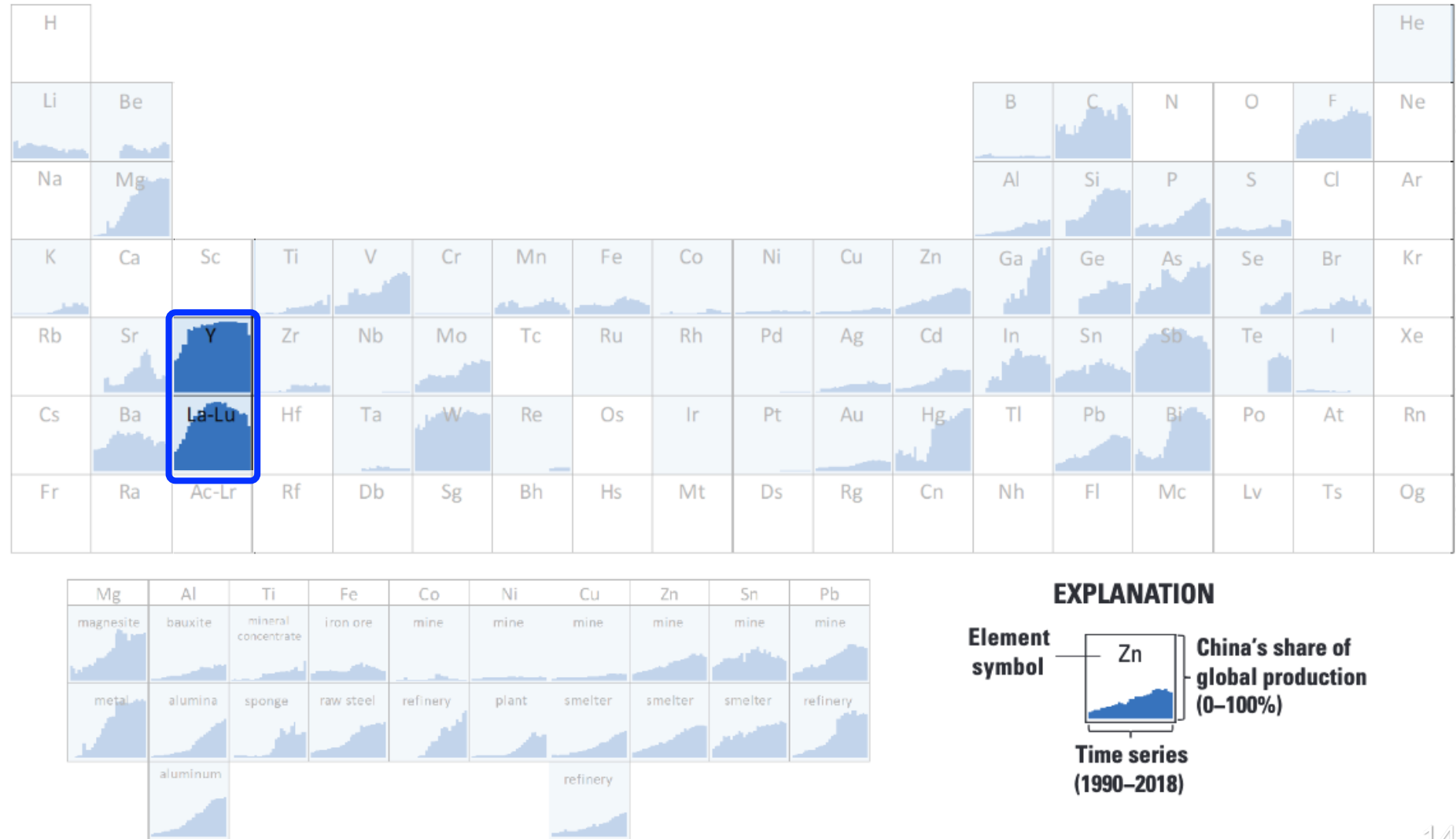
Rare Earth Reserves, by Country, 2019
(Metric Tons)

Country	Reserves
China	44,000,000
Brazil	22,000,000
Vietnam	22,000,000
Russia	12,000,000
India	6,900,000
Australia	3,300,000
Greenland	1,500,000
U.S.	1,400,000
Tanzania	890,000
Canada	830,000
South Africa	790,000
Other countries	310,000
Total	115,920,000

Source: U.S. Geological Survey

Markets: China dominates global production of REEs

- Averaging greater than 90% of global production from 1988 to 2016
- Has reduced to ~62% of global production
 - Strategic domestic stockpiling
 - Producing more final products, e.g., NdFeB permanent magnets with minimal import tax



Project tasks: Task 4

Provide a historical perspective of the quantity of all 37 CMs produced off-shore since 2000, and projected market potential through 2035. Similarly, provide a historical perspective that identifies the quantity of all 37 CMs imported currently to the U.S, as well as a projected market potential through 2035.

- Prioritizing demand driving markets in the short term
- Adding long-term and future demand markets in Q3 of work
- Historic market reports, pricing trends, and commodity summaries

Rare Earth Production, by Country, 2019-2023
(Metric Tons)

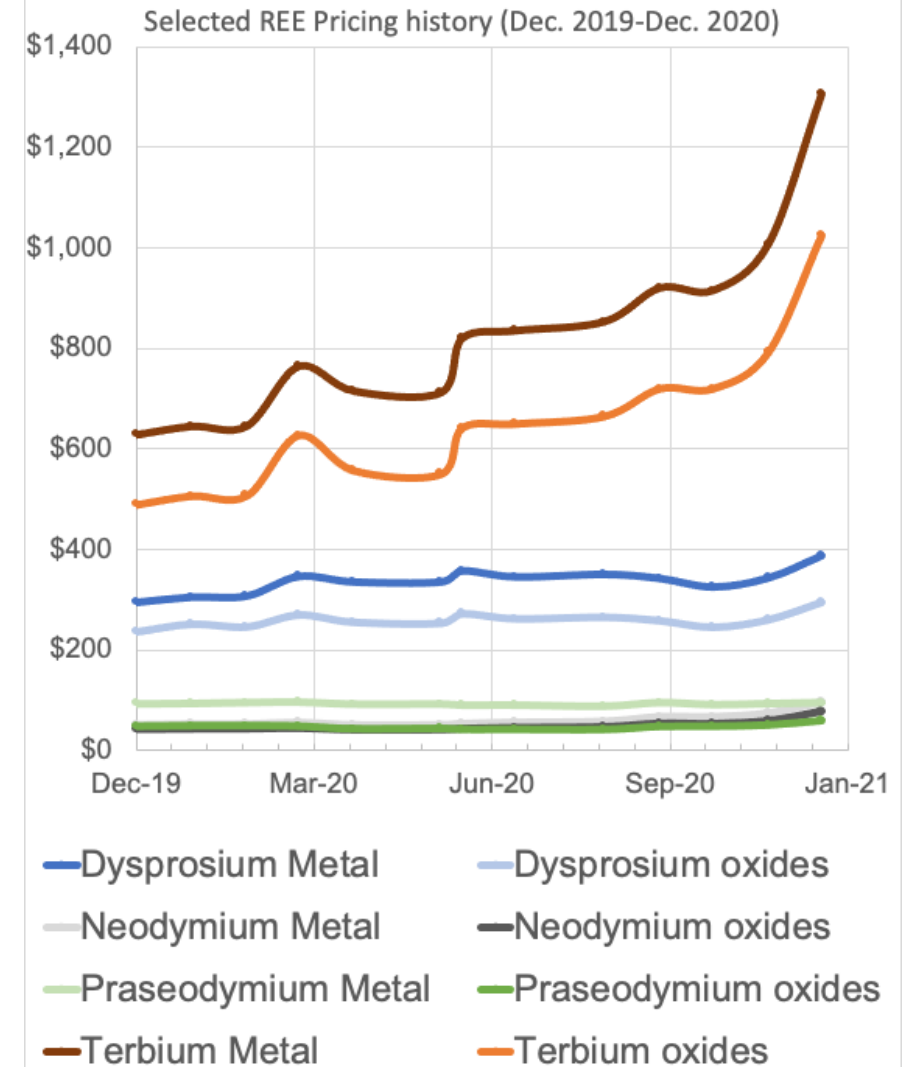
Country	2019	2020	2021	2022	2023
China	132,000	148,500	158,223	169,634	178,465
U.S.	26,000	29,250	33,656	37,504	41,016
Burma (Myanmar)	22,000	24,750	28,099	31,112	33,814
Australia	21,000	23,625	25,746	27,930	29,744
India	3,000	3,375	5,597	7,142	8,767
Russia	2,700	3,038	4,346	5,292	6,262
Madagascar	2,000	2,250	2,978	3,523	4,070
Thailand	1,800	2,025	3,252	4,110	5,010
Brazil	1,000	1,125	1,755	2,199	2,661
Vietnam	900	1,013	1,360	1,618	1,879
Burundi	600	674	972	1,188	1,408
Total	213,000	239,625	265,984	291,252	313,096

Source: BCC Research

15

Historic pricing trends

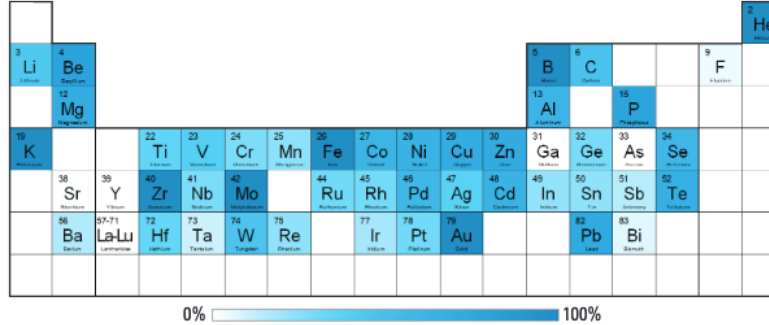
- Analyze historic and current REE and CM pricing trends



U.S. REE consumption is heavily import reliant

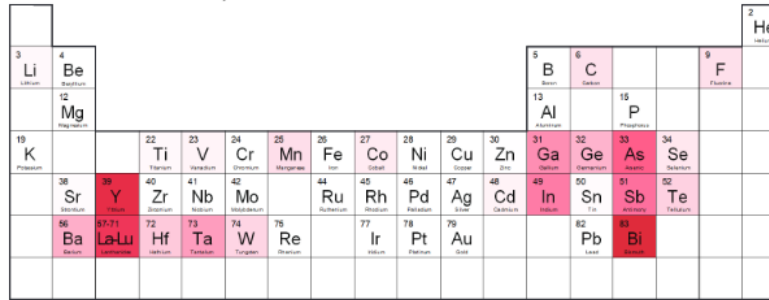
- No primary production of 22 minerals on CM list
- Limited to byproduct production of 5 minerals

A. Domestic sources and partner countries



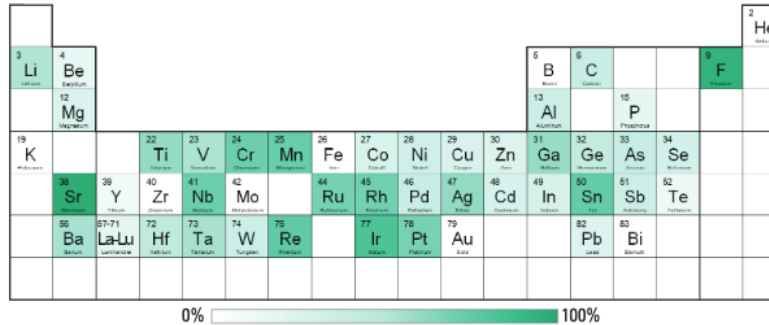
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B. Nonmarket economy countries



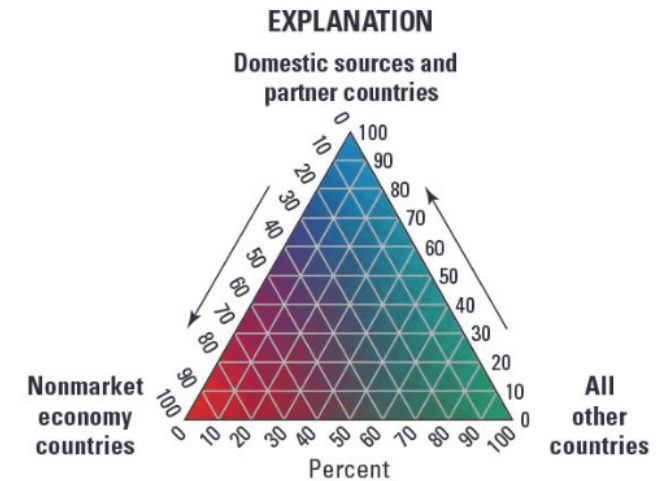
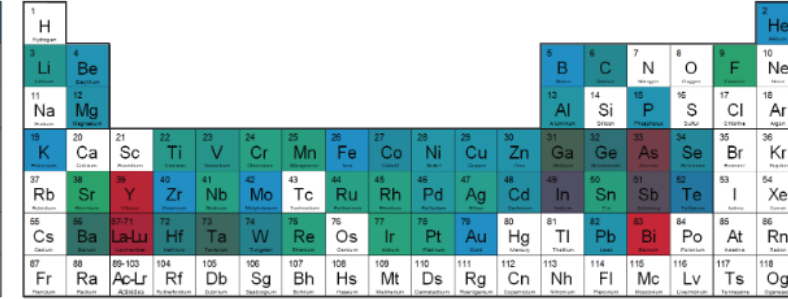
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C. All other countries



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D. Overall

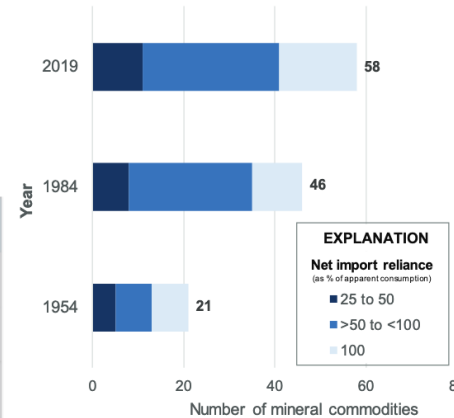
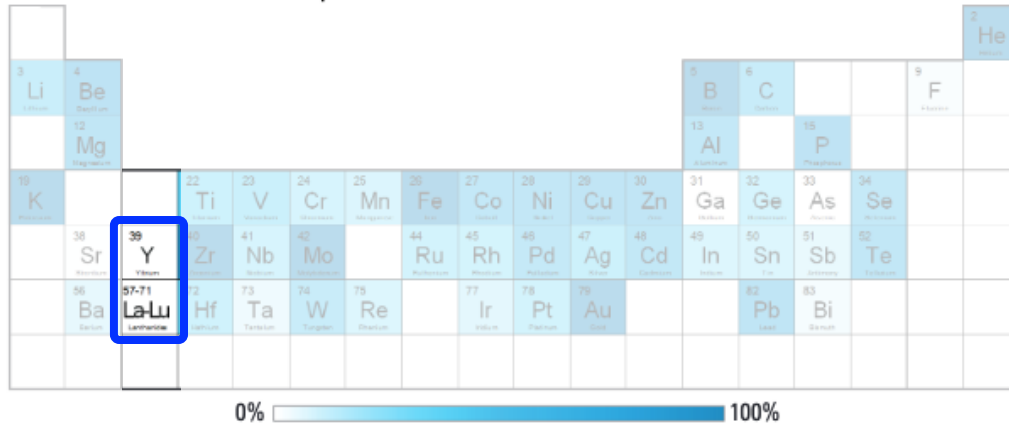


USGS, Investigation of U.S. Foreign Reliance on Critical Minerals¹⁷

U.S. REE consumption is heavily import reliant

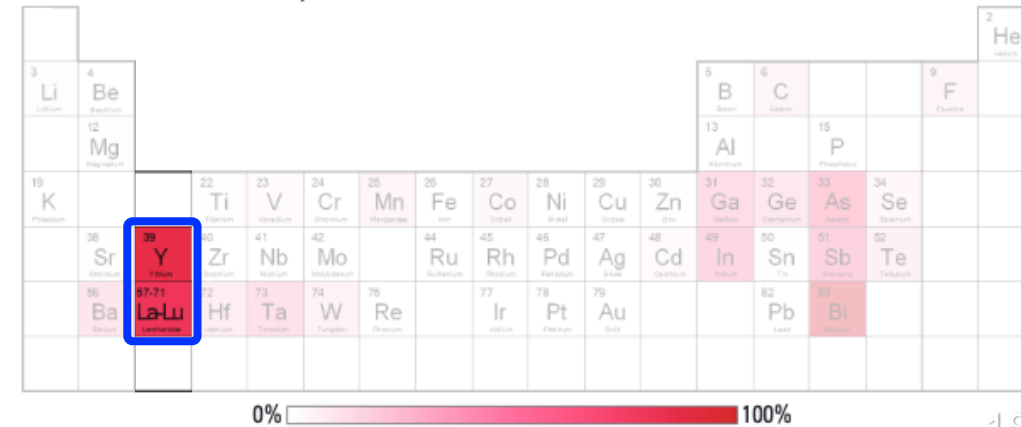
- Minimal U.S. domestic or partner country production of REEs
 - Increasing efforts to identify global sources and refining capabilities
 - Refining is capital cost intensive
- Favorable pricing strategies in China
 - FOB vs. Domestic price
 - Limited incentives in U.S.

A. Domestic sources and partner countries



USGS, Investigation of U.S. Foreign Reliance on Critical Minerals

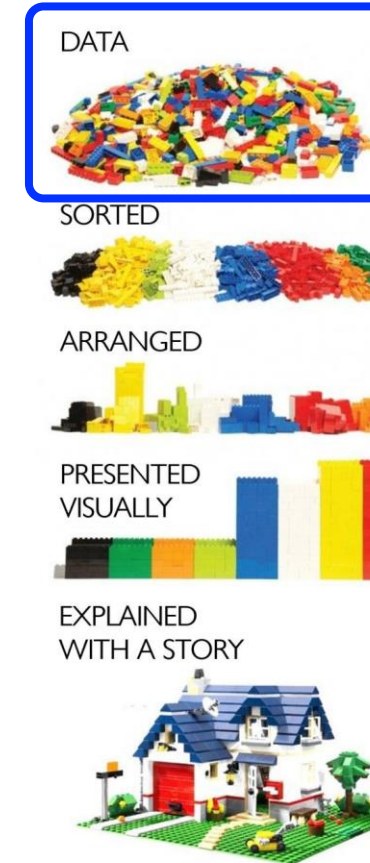
B. Nonmarket economy countries



Project tasks: Task 5

Identify the top 10 most imported products to the U.S. that contain CMs.

- Data mining US Imports and Border Control
 - Port-level data (values and finished products)
- Data mining US Census & US BEA
 - End-use imports
 - Micro-level trade in goods and services



Current state

Uses: Industrial intermediates and final products

- Critical REEs more in demand for high-growth markets (ceramics, phosphors, metal alloys, and magnetics) and National Defense
- U.S. primarily consumes light REEs (Sc, Y, La, Ce, Pr, Nd, Pm, Sm, Eu, and Gd)
- Heavy REEs (Tb, Dy, Ho, Er, Tm, Yb, and Lu) amount to less than 2% domestic consumption



CERAMICS
Capacitors
Sensors
Colorants
Scintillators
Refractories



PHOSPHORS
Display Phosphors
— CRT, LPD, LCD
Fluorescents
Medical Imaging
Lasers
Fiber Optics



GLASS & POLISHING
Polishing Compounds
Pigments & Coatings
UV Resistant Glass
Photo-Optical Glass
X-Ray Imaging



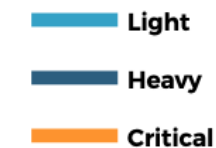
METAL ALLOYS
NiMH Batteries
Fuel Cells
Steel
Super Alloys
Aluminium/Magnesium



CATALYSTS
Petroleum Refining
Catalytic Converter
Fuel Additives
Chemical Processing
Air Pollutions Controls



MAGNETICS
Computer Hard Drives
Disk Drive Motors
Anti-Lock Brakes
Automotive Parts
Frictionless Bearings
Magnetic Refrigeration
Microwave Power Tubes
Power Generation
Microphones & Speakers
Communication Systems
MRI



NETL Infographic: Success in the Rare Earth Elements Program

Project tasks: Task 6

Identify the resource, location and quantity of all 37 CMs currently produced within the U.S. and the utilization of the CMs either domestically or as exports to produce intermediate and/or end-product materials, equipment, etc. throughout the entire global CM supply chain, and potentially future U.S. infrastructure needs for domestic production.

- Current work with Materials Flows through Industry tool and database to enhance REE data with flow through industry/products
- Structural path analysis of CMs using global Input Output economic models

Scenarios Product Recipes [Jarichter@psu.edu](#)

Product Recipes [BACK](#)

Name: ACID ROASTING, MONAZITE BASTNASITE
Description:
Owner: hzhang
Product: 32% REO RE2(SO4)3 FROM ACID ROASTING [+](#)
Process State Type: Public
Proprietary?:
Process Type:
Product Quantity: 1.0
Product Unit: Kilogram
Baseline Weight: 1.0
Source: REE TOOL FROM PURDUE

Materials

Material	Material Quantity	Material Unit	Byproduct	Fuel Use	Note 1	Description
50% REO CONCENTRATE FROM BENEFICIATION	0.6297230000000003	kg	No			
SULFURIC ACID	0.6926949999999995	kg	No			
FUEL OIL AND RESID	6.59	mj	No			heat production, heavy fuel oil, at industrial furnace 1MW

MFI Tool, c/o NREL

REE resource locations, US (not exhaustive)

New processing facilities in northern NV, TX, and near Atlanta, GA with international partners

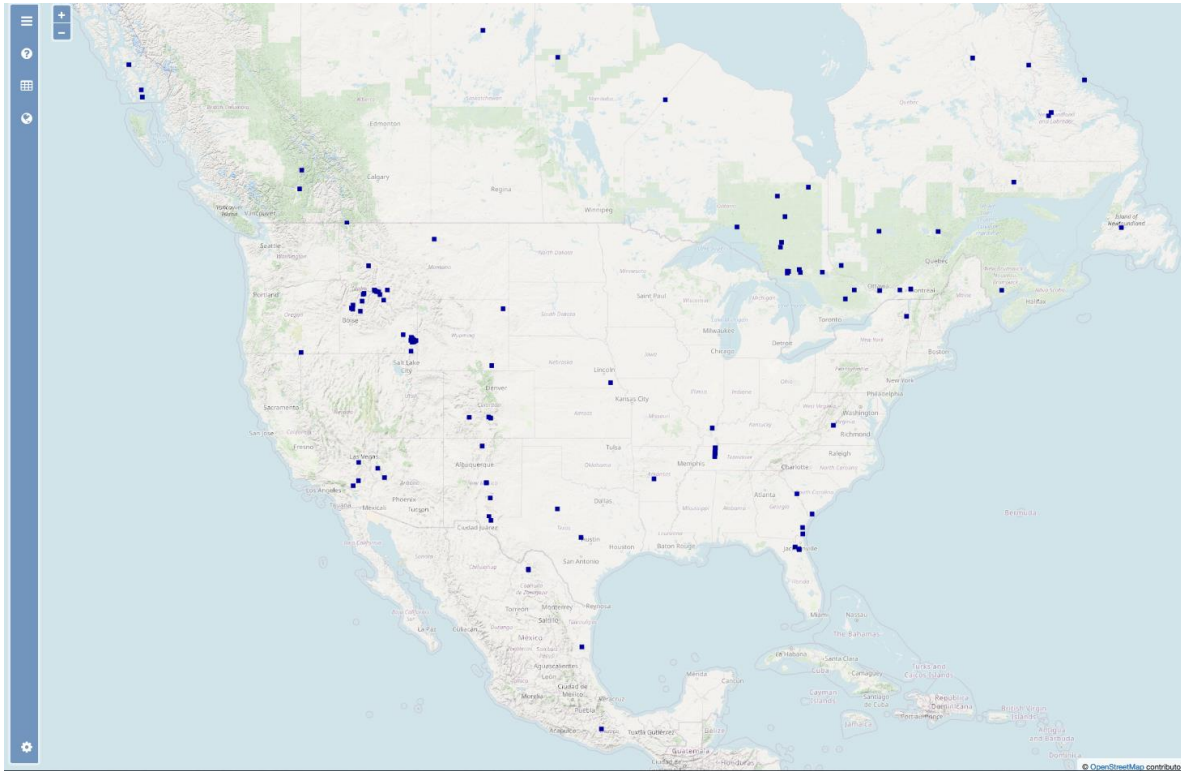


Table 26
U.S. Rare Earth Resources

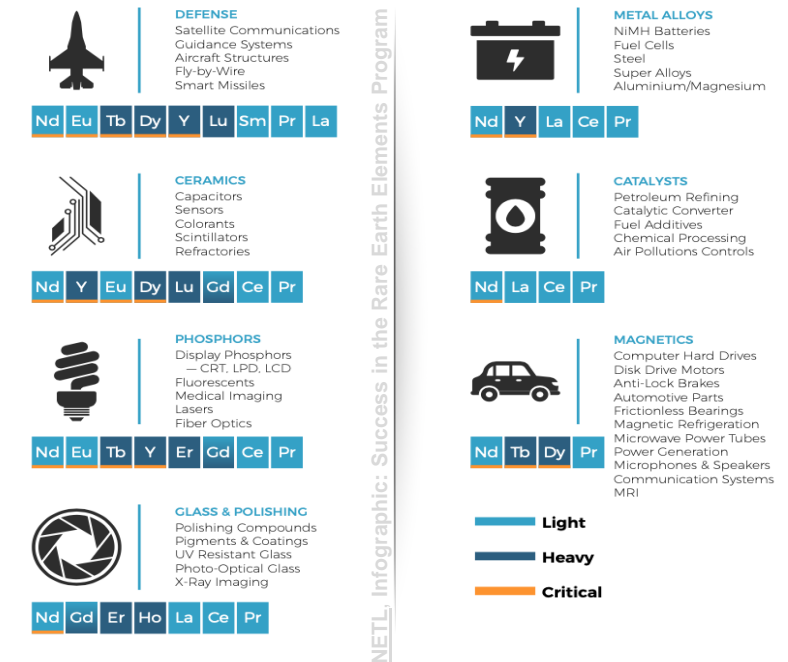
Main Deposits or Mines	Identified Resources (Mt)	Average REO Grade (%)	REO Content (t)
Iron Hill, CO	1,105.6	0.57	6,350,000
Mountain Pass, CA	18.4	7.98	1,470,000
Bear Lodge, WY	51.7	2.75	1,424,000
Round Top Mountain, TX	821.7	0.06	519,300
Elk Creek, NE	83.3	0.44	366,500
Lehmi Pass, ID/MT	61.9	0.52	321,700
Bokan Mountain, AK	34.3	0.50	171,500
Wet Mountains, CO	14.0	0.79	110,800
Mineville, NY	9.0	0.90	80,000
Pea Ridge, MO	0.6	12.00	72,000
Hicks Dome, IL	14.7	0.42	62,000
Scrub Oaks, NJ	10.0	0.38	38,000
Bald Mountain, WY	18.0	0.08	14,400
Other smaller deposits	—	—	18,000
Monazite deposits	—	—	450,000
Phosphorite deposits	—	—	110,000
Total	2,243.2	—	11,578,200

Source: BCC Research

Project tasks: Task 7

Identify the industrial opportunity for utilization of CM and CM-containing materials within the U.S. if a domestic supply of high purity CMs were to be available, and where it could be utilized to ensure that the CMs remain within the U.S.

- Revisiting demand driving markets
- Research to be done on replaceability
 - Honda first electric motor REE free
 - Mahle, Turntide Technologies also
- Pending completion of Task 2 and Task 5



Additional supporting activities

- Research collaboration developed with former dissertation committee member research group
- Additional research proposal in development for Lithium production in U.S.
- Undergraduate researcher mentoring
 - Independent study for REE research

Acknowledgements

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