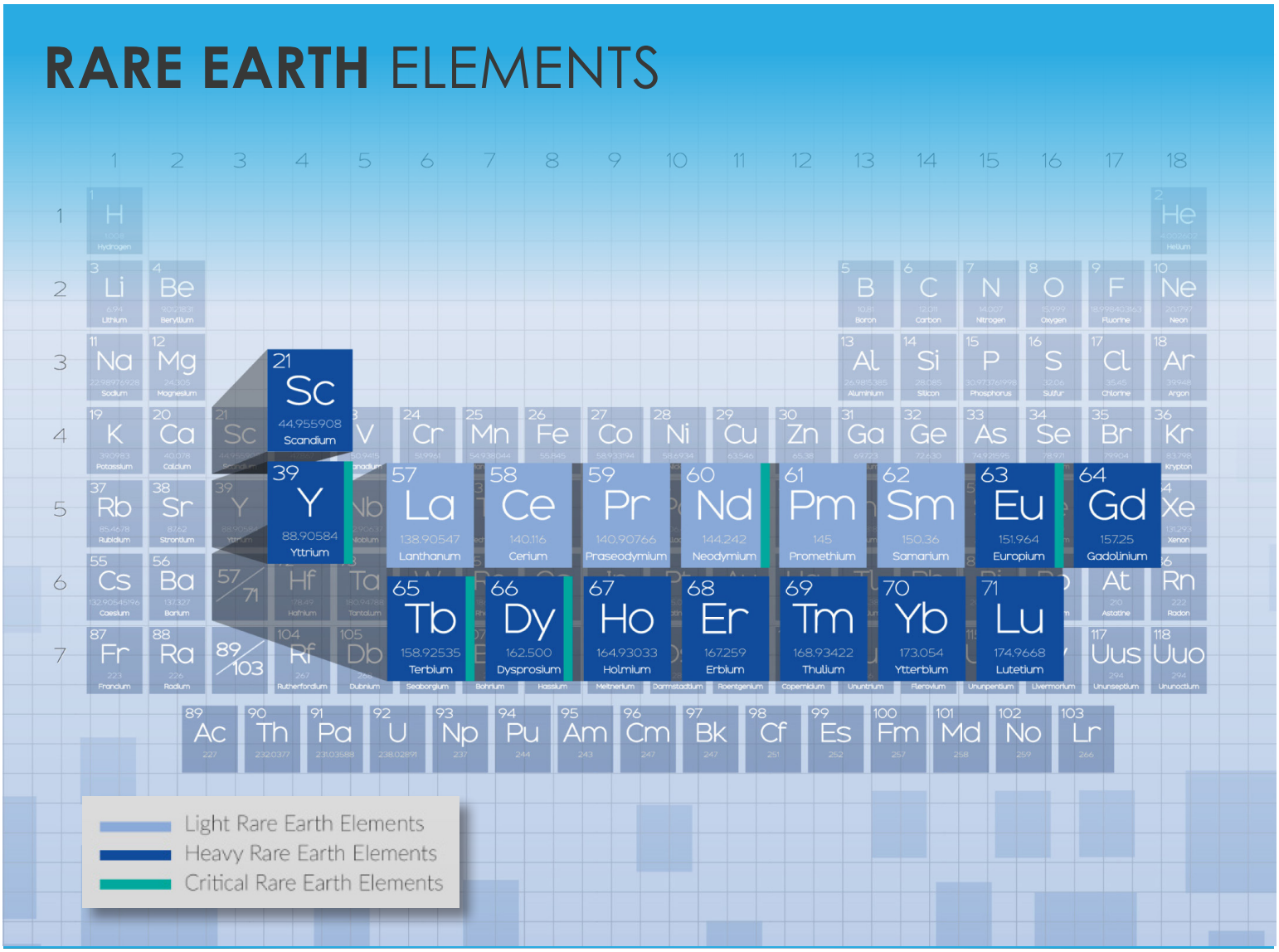
RARE EARTH ELEMENTS



NETL

NATIONAL ENERGY TECHNOLOGY LABORATORY

BACKGROUND

The U.S. Department of Energy Office of Fossil Energy conducts programs to ensure the availability of ultraclean (near-zero emissions), abundant, low-cost domestic energy from coal. These efforts are designed to fuel economic prosperity, strengthen energy independence, and enhance environmental quality. As the Office of Fossil Energy's research laboratory, the National Energy Technology Laboratory (NETL) is engaged in research, development, and demonstration (RD&D) activities to create technology and technology-based policy options for public benefit.

As part of its RD&D technology portfolio, NETL has initiated the Rare Earth Elements (REEs) from Coal and Coal By-Products RD&D Program, which focuses on development of REE separation and recovery technologies, addressing the current global REE separations market and process economics, and demonstrating the generation of environmentally benign REE separation processing capabilities. The quantities of REEs in our nation's vast coal resources offer the potential to reduce U.S. dependence on foreign sources for these critical materials, and to create new industries in regions where coal plays an important economic role.

RARE EARTH ELEMENTS PROGRAM

Since 1988, China has been the dominant supplier of REEs. In 2011, China provided 95 percent of the global market and decided to restrict exports and favor its own domestic industries—a decision that resulted in REE price volatility. Consequently, rising concern among industrialized nations has revitalized global interest in REE mineral exploration and extraction, and related research on supply, demand, utilization, recycling, reuse, and substitution. Worldwide, several new commercial REE projects, in various stages of planning and development, are focused on diversifying supply; however, new efforts to purify and refine REEs remain limited.

In 2009, intensified interest in strategic materials culminated in discussions regarding our nation's ability to secure reliable supplies of REEs and other strategic materials. Strategic materials were identified as critical for growing the U.S. green energy and electronics industries, as well as for specialty military applications (Figure 1). In response, DOE released the first Critical Materials Strategy in 2010, identifying yttrium (Y), neodymium (Nd), europium (Eu), terbium (Tb) and dysprosium (Dy) as critical REEs. NETL subsequently began exploring extraction of REEs from coal and coal by-products. Recognizing the importance of this resource to U.S. economic security, Congress appropriated funding during fiscal year 2014 to identify the magnitude of the resource, develop capabilities to economically recover rare earth metals in an environmentally responsible manner, and provide an additional domestic resources that would be secure and reliable for future advanced technology industries in the United States. In 2015, NETL launched internal R&D efforts to identify and locate domestic reserves containing elevated REE concentrations in coal and coal-related materials. NETL also began to explore commercial and novel transformational REE separation and extraction concepts, and to address REE separation technology performance and process economics. During fiscal years 2015 and 2016, NETL expanded these efforts, providing funding opportunities to external industry and university partnerships to assess U.S. coal-based resources containing high amounts of REEs, and to address REE separation and extraction in bench and pilot-scale facilities. Working in collaboration with the DOE Office of Fossil Energy, NETL plans to issue a funding opportunity to solicit projects for the production of coal-based, high-purity, salable REEs. In addition, during 2017, NETL plans additional collaborative efforts in the areas of advanced REE separation concepts, field technology development, and in-process sensor technology development.

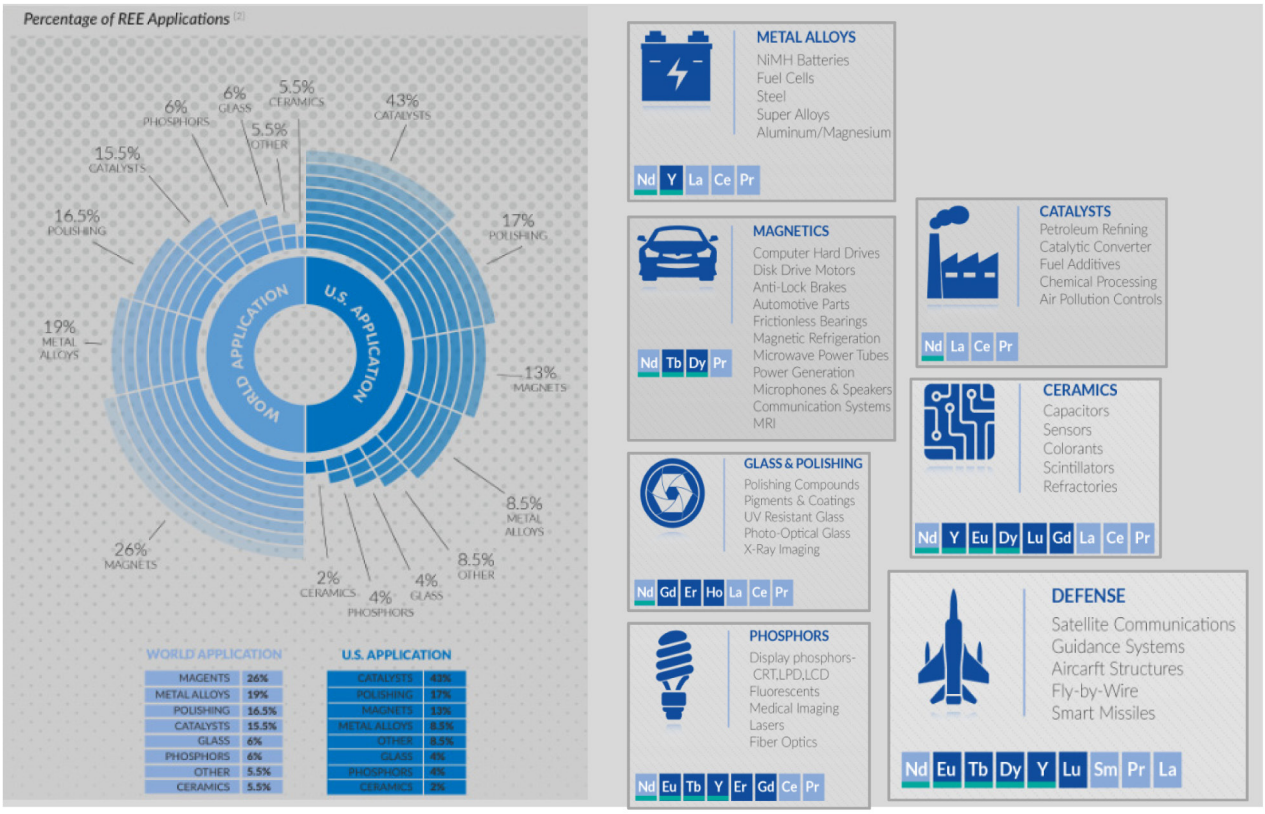


Figure 1.

PROGRAM OBJECTIVES

The overall objectives of NETL's REE program are to demonstrate the techno-economic feasibility and performance of existing commercial or newly developed REE separation technologies. These technologies are focused on separating and recovering REEs from coal and coal by-products containing a minimum of 300 ppm total REEs, and concentrating the REEs to levels greater than or equal to 2 wt%, tentatively producing 90–99.99% high-purity, salable, individual rare earth metal oxides by the year 2020. This will be accomplished through laboratory REE separation projects and demonstration of concept feasibility at bench-scale through pilot-scale facilities and integrated processing systems. Ultimately, these efforts will ready REE separations technology for commercial deployment. Key areas of success for this program include co-production of materials and critical elements, successful demonstration of environmentally benign processing, and competitive economics.

CORE TECHNOLOGY AREAS

The REE program consists of three core technology areas: Enabling technologies, Separations Technologies, and Process System Development (Figures 2 and 3).

- **Enabling Technologies** include resource identification, sampling, and characterization; techno-economic analysis; and field/process sensor development.

  Significant progress has been made in locating field sites and assessing composition of potential coal and coal by-product materials containing REEs. Continued effort is focused on identifying the best source of materials to support future commercial REE production. Chemical and physical characterization efforts, addressing REE elemental concentrations and phase compositions in the coal and coal by-product resources, are essential in the development of viable REE separation processes.

  Techno-economic analyses are being conducted to evaluate the international REE market demand and to assess the economics of commercially producing REEs from conventional separation, as well as potentially new advanced transformational separation processes. A preliminary, high-level REE jobs analysis is being developed that includes an estimation of the economic impacts of constructing and operating an REE separations and processing facility (or facilities) in the United States.

  Development of portable sensors for identifying promising REE coal-based resources in the field, as well as devices for determining REE concentrations in process separation flow streams is being evaluated. Tentatively these technologies will be tested in the field, at bench-scale separations test facilities, and validated to commercial-ready status during use in pilot-scale demonstration projects.

- **Separations Technologies** include utilization or modification of currently available, commercial, physical separation systems (i.e., beneficiation via size, density, froth flotation, magnetic, ultrasound), hydrometallurgy and solvent extraction/digestion processes, and pyrometallurgy techniques (i.e., electro-slag refining, acid roasting) to separate and concentrate REEs from

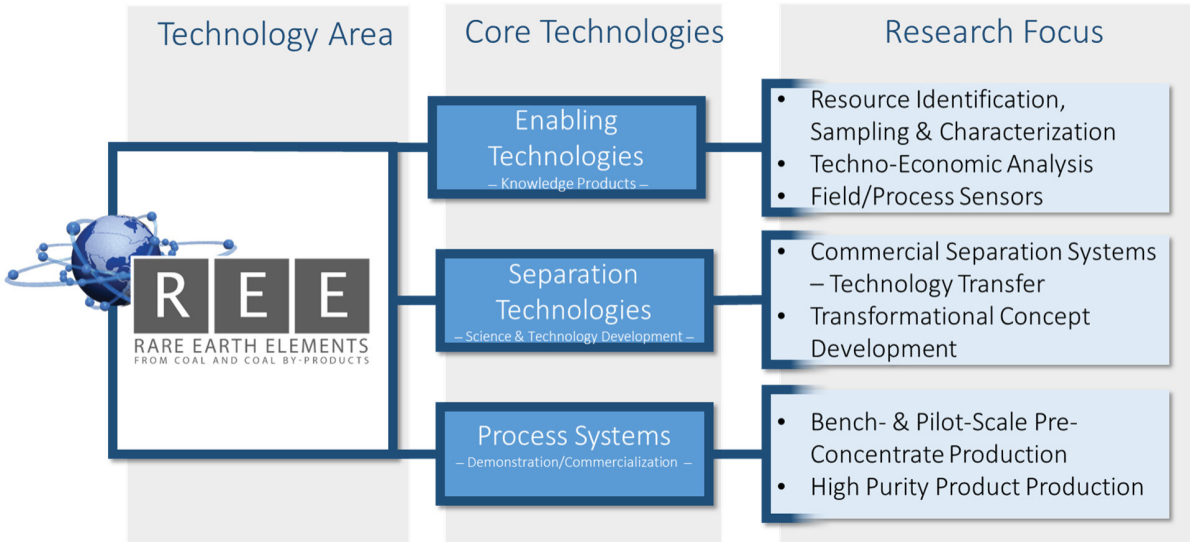


Figure 2.

Figure 3.

coal-based resources such as coal, coal refuse, clay/sandstone over/under-burden materials, aqueous effluents, acid mine drainage sludge, and power generation ash. Advanced or new transformational REE separation concepts such as physical, chemical, electrical and thermal extraction, acid/base leaching, and ion exchange; reactive grinding, photochemical, ultrasonic-assisted, microwave-aided, photophoretic, plasma, and supercritical CO_2 separation; as well as advanced sorbents and membrane systems, are being considered to further enhance REE separation.

- **Process System** demonstration and commercialization include validation of bench and pilot-scale separation performance and economic feasibility to achieve separation and concentrating REEs contained in 300 ppm coal and coal-related resources, to an initial pre-concentrate matrix containing greater than or equal to 2 wt%, with integration of further extraction systems that lead to the generation of high-purity, salable rare earth compounds (such as oxides and/or metals, carbonates, etc.).

Ultimately, domestic generation of high-purity REEs, may return production of REE-containing materials to the United States, providing national security and stimulating economic growth. Futuristically, domestic REE generation is envisioned to advance U.S. on-shore manufacturing of REE-containing parts, equipment, and end-products such as wind turbines magnets, automobile engines, cell phones, computers, satellites, and the like. REE generation also supports alternate industry and technology needs for processes such as catalysis, alloy and high-temperature coatings development, petroleum refining, battery development, medical equipment, defense, and so on. In addition, an available domestic supply of REEs may lead to commercialization of new, advanced materials and equipment.

Additional information can be found on NETL's Rare Earth Elements web page and energy data eXchange (EDX) database.

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