# NETL EDGE

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# CRITICAL MINERALS FOR A CLEAN ENERGY FUTURE

NATIONAL ENERGY TECHNOLOGY LABORATORY

# ON THE COVER

Rare earth elements are essential materials that are incorporated into many of today's components and are paving the way for future innovations. The DOE-NETL Critical Minerals and Materials Program is focused on extracting, separating and refining rare earth elements and critical minerals from carbon-based resources and other non-traditional feedstocks.

# DIRECTOR'S MESSAGE

British chemist Sir William Crookes had an interesting take on rare earth elements (REEs) — those 17 elements on the periodic table that play such a critical role in everything from national security and energy independence to consumer products and economic growth:

"The rare earth elements perplex us in our researches, baffle us in our speculations, and haunt us in our very dreams" he wrote around the turn of the 20th century. "They stretch like an unknown sea before us mocking, mystifying and murmuring strange revelations and possibilities."

More than 100 years after Crookes expressed his wonder over the "strange revelations and possibilities" of REEs, the researchers of NETL continue to make progress in the drive to find ways to retrieve them from where they lie.

REEs really aren't that rare. The U.S. Geological Survey describes them as "relatively abundant in the Earth's crust." What makes them "rare" is the fact that they are jumbled together with many other minerals in different concentrations like carbon ore. Currently, the U.S. imports most of the REEs needed for a wide range of national defense and consumer products.

That's where NETL's efforts come in. Our talented researchers, with a focus on recovering REEs from their "jumbled" environments, have made significant strides in detecting and retrieving them from unlikely sources. In this issue of Edge, we bring that progress to light for our readers.

In this issue, readers will learn about how we are assessing the economic viability of recovering REEs from unconventional feedstocks like coal and coal waste; discovering platinum group minerals from ultramatic rocks; removing aluminum that hinders recovery of REEs; bringing transformational change to the Wyoming Powder River Basin; finding ways to revitalize historic energy communities by using new REE detection systems; helping use the Bipartisan Infrastructure Law to start up the first wave of production facilities for critical minerals; and much more.

Readers will also find an informative interview with Jessica Mullen, one of our award-winning technology managers who has helped make key progress in uncovering technologies for advanced sensors, recovering of REEs from acid mine drainage and reducing water consumption at power plants.

Clearly, NETL remains at the forefront of the drive to recover REEs from unconventional sources. We are proud of that progress and committed to continuing the effort to make the U.S. a powerhouse source for critical REEs that help make important products, protect the nation and help in the effort to improve energy systems.

We hope you enjoy this edition of Edge.

Sean I. Plasynski, Ph.D.
*Director (Acting), NETL*

# TABLE OF CONTENTS



NETL ANSWERING A WORLDWIDE THIRST FOR

# CRITICAL MINERALS

WITH WORLD CLASS RESEARCH AND PERSONNEL

By Gerrill Griffith

An accelerating transition to electric vehicles as part of decarbonization activity and ever-expanding demand for a wide array of consumer products are fueling an aggressive search for domestic sources of critical minerals (CMs) that include rare earth elements (REEs) and platinum group minerals (PGMs). Both are critical ingredients of many key commodities.

NETL engages its considerable people talents and research facilities to identify promising unconventional sources for CMs like coal waste, create new ways to assess the feasibility for their recovery from those sources, and remove impurities that hinder recovery efforts.

REEs, for example, are a set of 17 metallic elements that are used in many high-tech devices. REEs are used in clean energy components like generators in wind turbines and electric vehicle motors in addition to defense systems, electronics and a large range of other consumer goods. The International Energy Agency estimates that demand for REEs may at least quadruple by 2040.

Meanwhile, PGMs, including iridium, osmium, palladium, platinum, rhodium and ruthenium, are among the rarest mineral commodities in the Earth's crust and are attracting increased attention for use in a wide range of applications like medical implants such as pacemakers and cancer-fighting drugs.

The United States currently imports nearly all its supply of CMs including REEs and PGMs. According to the U.S. Geological Survey (USGS), China was the leading import source for gallium, germanium and graphite; Norway was the leading source for cobalt; Argentina for lithium; Gabon for manganese; Canada for nickel; and South Africa for platinum.

A 2021 executive order noted that critical mineral supply chains have the potential to be disrupted by adverse foreign actions, pandemics, natural disasters and other global events. "For this reason, the development of domestic resources to secure supply chains and meet future CM demand has become a national priority."

NETL is contributing to the work of securing new domestic sources for the CMs that are so much a part of everyday lives.



## NETL's Framework for Assessing the Feasibility of Recovering REEs from Unconventional Sources

NETL recently created a framework to assess the economic viability of recovering REEs from unconventional feedstocks like coal and coal waste — an advancement that is part of NETL efforts to unlock new domestic sources of CMs that can ease the nation's dependence on foreign sources for the minerals.

Until now, the economic viability of recovering critically needed REEs from unconventional sources has remained difficult to determine.

In a new article appearing in the respected Nature Sustainability publication, NETL experts Alison Fritz, Ph.D., and Thomas Tarka and Stanford University's Megan Mauter, Ph.D., describe their work to create a new framework for assessing the economic viability of unconventional REE feedstocks.

"There's no doubt that sourcing REEs from unconventional feedstocks like secondary waste materials could have substantial environmental and societal–economic benefits if executed correctly," Fritz, who served as the primary author, explained. "But its economic viability remains unclear. Without some clear metrics to evaluate recovery efforts, it is hard for industry leaders to understand whether the economics of important projects make sense."

Fritz said NETL created a framework to answer economic viability questions.

"We started by developing an effective database of capital and operating expenses for REE recovery," she said. "That allowed us to establish consistent process unit costs for common stages in the conventional supply chain. We then used market prices to develop well-defined methods for determining diverse product values."

According to a DOE report to Congress about REEs in 2022, "DOE has made many advancements toward the recovery of REE and CM from coal and coal byproducts — identifying significant REE resources in coal and coal byproducts and in what quantities and combinations; demonstrating that they can be extracted from coal, coal measures, coal ash, coal refuse and acid mine drainage; and establishing first-of-a-kind pilots that produce high-purity REE from these feedstocks."

Tarka explained that NETL's economic analysis work is a natural follow-on to ongoing research and can help facilitate the shift to alterative REE sources.

"The success of REE recovery efforts require an understanding of the cost for production of a mixed rare earth product, either in the form of a pregnant leachate solution or a solid material, which we define as extraction and processing costs," he said. "It also requires cost estimates for upgrading the mixed material to saleable products, which we define as refining costs. Finally, it requires consistent assumptions about the market value of rare earth products and the effects of economies of scale and feedstock purity on capital and operating costs."

Fritz added that published information on aspects of the stages of commercial REE production is inconsistent.

"In the absence of strong data on process costs, previous techno-economic assessments of unconventional feedstocks make highly inconsistent assumptions about refining costs and the appropriate discount applied for low-purity REE products," she said. "This inconsistency stymies comparisons between techno-economic assessments. We believe our framework can help correct those deficiencies."

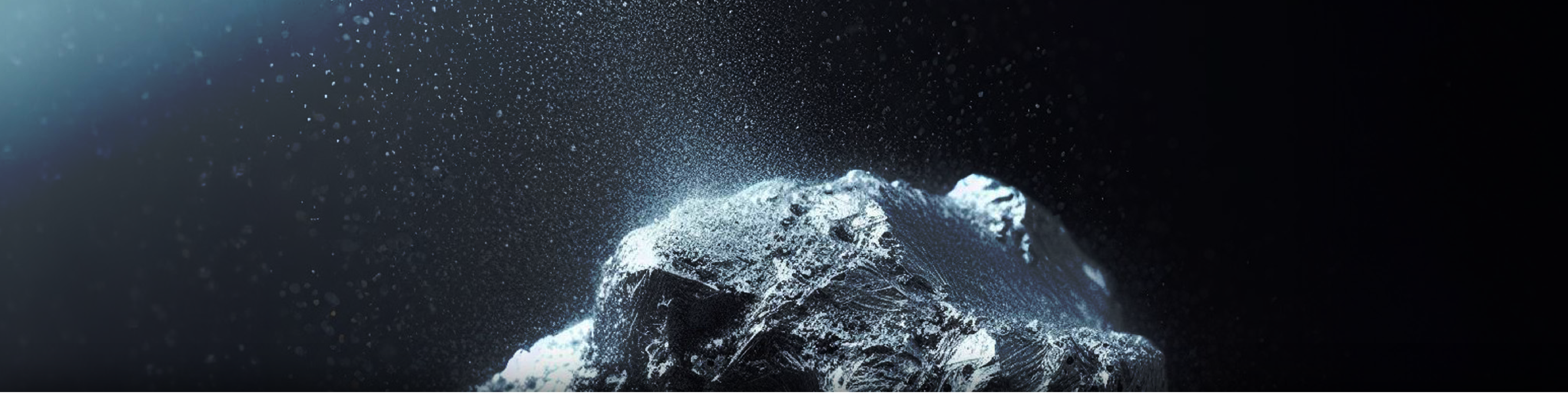
The economic analysis work complements a range of significant progress made possible by NETL research. The lab has built strong partnerships with industries that are making considerable advances in the field.

NETL also developed and publicly released the Unconventional Rare Earth and Critical Materials Assessment Method, a big data approach to prospect for critical minerals resources associated with sediments.

Furthermore, NETL also published a study that demonstrated the Lab's techniques can accurately analyze and assess coal-related core materials. The methodology in the paper supports the development and curation of big-data-driven, geospatial modeling to help beneficiate and optimize REE and CM potential from primary (carbon ore) and secondary (byproducts and waste streams) sources.

"At present, there is no systematic method or approach to predict and identify REE and CM resource potential and occurrence from sedimentary systems, carbon ores or mine waste streams," said NETL's Scott Montross, who is the lead author of the paper and was recently named as a technology manager for the Lab's Critical Minerals and Materials program. "This lack of a systematic assessment method inhibits our ability to predict where these occurrences are likely to be found and quantify the in-place or economically accessible volumes of unconventional REEs and CMs in these domestic resources."

*Continued on page 8*



## Discovery of Platinum Group Minerals in Ultramafic Rocks

When NETL researchers began to research the potential to recover CMs from rocks that are processed to remove atmospheric carbon dioxide in a practice called mineral carbonation, they expected to find valuable commodities like chromium, cobalt and nickel. But their work also discovered valuable quantities of PGMs, which are critical for the clean energy economy.

The finding could have positive implications for both the CM supply chain and an evolving decarbonization technology.

The discovery was a byproduct of research at NETL in Albany, Oregon. The federally funded research focused on pulling CMs from ultramafic rocks before they are subjected to enhanced mineralization or natural weathering — processes that accelerate the decomposition of calcium and magnesium-rich silicate rocks and a chemical reaction that removes carbon dioxide from the atmosphere.

Ultramafic rocks contain minerals that are naturally highly reactive to carbon dioxide. Researchers believe that enhanced mineralization can help stabilize and permanently store carbon dioxide.

The samples NETL examined came from the Twin Sisters mine in Washington's Whatcom County, a source for olivine, an abundant silicate found in Earth's mantle that is used to make molds that can endure high temperatures with low thermal expansion.

Millbank Materials, owners of the Twin Sister's mine, provided the Lab with access to the raw resources to test NETL mineralization and critical minerals technologies. Eion Carbon, a carbon removal company that focuses on enhanced rock weathering and NETL are working together in a cooperative research and development agreement to advance technology to remove critical minerals while preserving the mineral carbonation potential of the olivine from Twin Sisters Mine.

Circe Verba, Ph.D., of NETL's Center for Geological and Environmental Systems (GES) said "the breakthrough could help reduce reliance on foreign sources for PGMs by developing a sustainable domestic supply chain in conjunction with mineral carbonation waste streams."

"This research furthers the goals of the DOE Fossil Energy and Carbon Management Critical Minerals Sustainability Program," NETL's Burt Thomas said. "The team is focused on unconventional ores from waste streams we expect to grow in the future. This will hopefully lower the costs of mineral carbonation and provide secure sources of things like iridium, things that we know we are going to need a lot more of."

NETL's GES team tackles the challenges of clean energy production by focusing on the behavior of natural systems at both the Earth's surface and deep within the subsurface. With the laboratory equipment and computational models housed at NETL's facilities, researchers can peer into the subsurface to discover critical minerals and PGMs that have energy-related value.

Jon Yang, Ph.D., is the lead researcher on the project. He explained that PGMs are critical to manufacturing and automotive sectors as catalytic materials.

"For the green energy transition, platinum and iridium will be crucial for the developing green hydrogen technologies as catalysts for hydrolyzing reactions," he said. "Coupling the recovery of PGMs with actively mined rocks used in growing enhanced rock weathering industries significantly lowers the technological risks and cutoff grades for traditional PGM extraction."

According to the USGS Mineral Resources Program, PGM refining has traditionally been a complex process because the chemical similarities of the metals make their separation difficult.

USGS reports that since 1960, approximately 90% of global PGM production came from South Africa and Russia, with Canada, the United States and Zimbabwe accounting for 5%, 2%, and 1% of production, respectively.

Some examples of PGM applications include:

Platinum-based fuel cells are enabling mini-grid electrification technology that is an attractive and cost-competitive alternative to grid electrification in remote areas.

Because platinum is an effective catalyst in hydrogen-powered fuel cells, it is being used in new electric vehicles.

In the electronics industry, PGM components increase storage capacities in computer hard disk drives and are ubiquitous in electronic devices, multilayer ceramic capacitors, and hybridized integrated circuits.

The chemical industry uses platinum or platinum-rhodium alloys to manufacture specialty silicones and to make nitric oxide, the raw material for fertilizers, and nitric acid.

In the petrochemical industry, platinum-supported catalysts are needed to refine crude oil and to produce high-octane gasoline, in addition to making plastics, synthetic rubber and polyester fibers for clothing.

The glass manufacturing industry uses PGM to produce fiberglass and liquid-crystal and flat-panel displays.

PGM alloys are exceptionally hard and durable, making them the best coating for the industrial crucibles used to manufacture chemicals and synthetic materials, including the high-purity sapphire crystals used to make light-emitting diodes.

Because platinum does not corrode inside the human body and allergic reactions to platinum are rare, it is used in medical implants such as pacemakers. PGM are also used in cancer-fighting drugs.

Because platinum, in certain chemical forms, can slow or stop the division of living cells, platinum-based drugs are being developed to treat cancers.

Platinum-cured silicones can coat and protect automotive air bags and keep them stable and folded for long durations without deteriorating.

Platinum-cured silicone mixes are used in lipsticks, shampoos, and contact lenses.

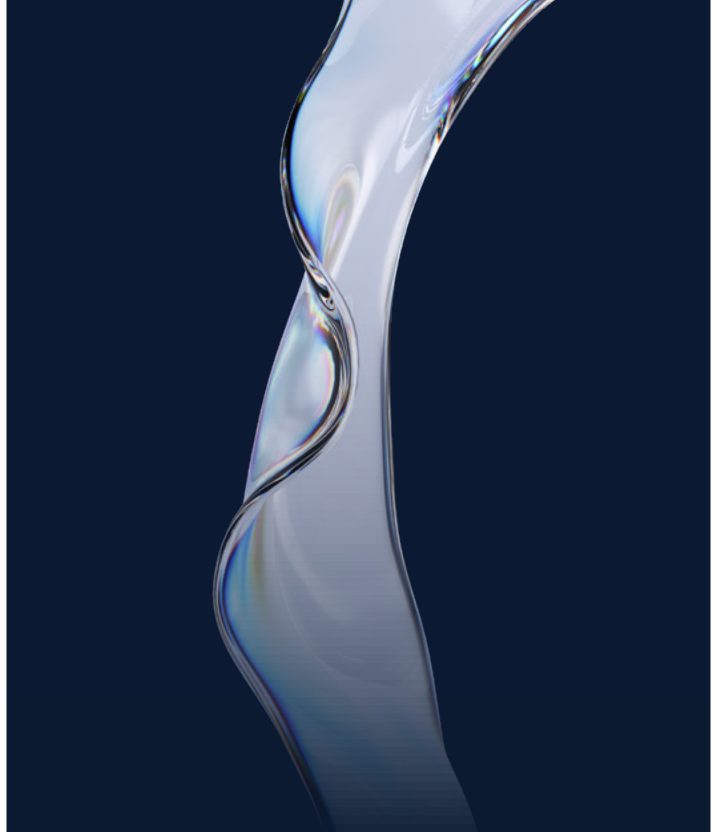
*Continued on page 10*

## Detecting and Removing Aluminum for Effective Recovery of REEs

Aluminum is a critical element used in thousands of important products, but it can often interfere with quick and effective extraction of REEs from coal waste byproducts.Because aluminum interferes with the recovery of REEs from some sources, NETL researchers developed an effective, renewable technology that can detect aluminum in liquids for removal, clearing the way for effective recovery of REEs.

The importance of securing more domestic REEs is reflected in investments in recovery technologies. Since January 2021, DOE has invested $25 million in 21 projects in Appalachia, the Gulf Coast, and other West and Midwest locations to support the production of REEs and critical minerals in traditional fossil fuel-producing communities across the country. DOE also recently announced up to $156 million in funding from the Bipartisan Infrastructure Law for a first-of-a-kind facility to extract and separate REEs and critical minerals from unconventional sources like mining waste.

In coal waste byproduct feeds, the concentration of aluminum is often significantly higher than that of REEs, and the presence of aluminum can interfere with REE extraction and purification processes. Therefore, the detection of impurities such as aluminum is very important during REE processing. Impurities can be divided into two groups according to their value: low-value elements and high-value elements. Aluminum and iron represent typical low-value elements often associated with REEs in primary and secondary raw materials.

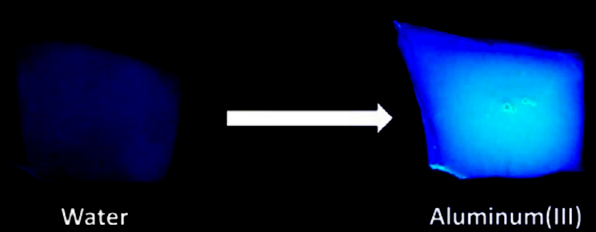


The new NETL-developed sensing material is a metal-organic framework thin film made of copper linked by 2-aminoterephthalic acid. The high-quality film can be grown within 30 minutes using a metal oxide template at room temperature, which eliminates the need for external heating or specialized equipment. The film emits blue light in the presence of water and becomes significantly more intense in the presence of aluminum ions.

As a proof-of-concept, the manufactured sensing films were tested on three fly ash leachates, and the fluorescence intensity correlated well with the aluminum concentration in the samples, highlighting the sensor's potential for real-world use. The same sensing film may also be recycled for multiple sensing cycles. Taken together, the NETL work presents a simple, scalable method for fabricating high-performance sensors to detect aluminum in solutions.

NETL researchers Scott Crawford, John Baltrus, Ki-Joong Kim, and Nathan Diemler developed the highly sensitive material that can be used to detect part-per-billion concentrations of aluminum.

In addition to detecting an impurity in REE feedstocks, removing and refining aluminum from liquid sources can also provide an additional domestic source of the raw material for the aluminum industry.




According to the USGS, "Aluminum is the second most abundant metallic element in the Earth's crust after silicon. It weighs about one-third as much as steel or copper; is malleable, ductile and easily machined and cast; and has excellent corrosion resistance and durability. Measured either in quantity or value, aluminum's use exceeds that of any other metal except iron, and it is important in virtually all segments of the world economy.

Some of the many uses for aluminum are in transportation (automobiles, airplanes, trucks, railcars, marine vessels), packaging (cans, foil), construction (windows, doors, siding), consumer durables (appliances, cooking utensils), electrical transmission lines, machinery and many other applications." ☰

NETL researchers led by Jon Yang, Ph.D., discovered platinum group minerals – extremely rare mineral commodities used in industrial applications and consumer products – in samples from the Twin Sisters olivine mine in Whatcom County, Washington.

# 'Use-the-Whole-Bison' Approach

## Guides NETL To Extract Rare Earths From Wyoming Coal Ash

**By Martin Kinnunen**

NETL's Christina Lopano appreciates and respects the history of the American West and is using that knowledge as her team brings transformational change to the Wyoming Powder River Basin (WPRB), the nation's top coal-producing region.

North American tribes who once lived here relied on the American buffalo to survive, and the animal was held in such high esteem that it played a major role in the spiritual life of many people. They also used nearly every part of the animal for food and to make clothing, shelter, tools and more.

**"We are committed to taking this same use-the-whole-bison approach,"**

said Lopano, an award-winning scientist, explaining the Lab's strategy to develop and deploy its Targeted Rare Earth Extraction (TREE) process in the WPRB.

The TREE process extracts rare earth elements (REEs), which are needed to protect U.S. energy, economic and national security, from coal and coal byproducts. In addition to REE extraction, NETL researchers are investigating to determine if minerals and other materials produced during the TREE process can be used for other purposes, such as helping to sequester greenhouse gas in the subsurface or to make roads safer for winter driving.

"Our goal is to use everything we extract or produce through the TREE process in order to minimize waste byproducts that would go to landfills," Lopano said.

The development of the NETL technology could also bring economic opportunities for communities in the 20,000-square-mile WPRB by transforming it from a region tied to producing fossil fuels into a supplier of REEs to serve many growing and vital U.S. industries.

REEs comprise only 17 elements from the entire periodic table, but they are needed to manufacture nearly all high-tech consumer products, including cellular telephones, computer hard drives, electric and hybrid vehicles, and flat-screen monitors and televisions.

The defense industry relies on rare earths to develop guidance systems, lasers and radar and sonar systems. REEs are key to the manufacturing of clean energy technologies such as solar panels, wind turbines and hydrogen fuel cells to meet the goals of the nation's historic climate agenda.

Currently, the United States imports more than 80% of its rare earth demand from non-domestic suppliers. TREE has been advanced to help develop a robust domestic REE supply chain and reduce U.S. reliance on foreign suppliers.

The TREE process, an environmentally friendly and cost-effective technology to extract targeted supplies of REEs from coal wastes, was invented by Lopano and NETL researchers Mengling Stuckman and Thomas Tarka.

Small, bench-scale studies of the technology have been completed. Additional research efforts into finding productive uses for byproducts generated by the TREE process are led by NETL colleagues Jonathan Yang, Jason Cheng, Colleen Hoffman, Ward Burgess and Alison Fritz.

"TREE uses a mild extraction methodology to recover extremely valuable materials while addressing environmental issues caused by landfilling this waste," Lopano said. "Furthermore, TREE employs ambient temperatures and pressure, requires almost no material preprocessing and reduces amounts of acids and organic solvents required downstream in the purification process."

The NETL team has found that TREE is particularly effective at extracting REEs from WPRB coal fly ash. Planning is underway to complete a small-scale pilot of the TREE process next summer at the Wyoming Innovation Center (WyIC) located in the community of Gillette in northeast Wyoming.

The WyIC opened in June 2022, with NETL as its first tenant. The center includes office, lab and workspace for researchers. The main draw, however, is the seven demonstration sites that function as an open-access platform for tenants to upscale their lab-proven processes from using a few pounds of coal or ash a day to processing up to several hundred pounds of coal or coal byproducts daily.

Current methods and technologies for REE extraction from carbon ore and ash sources can be expensive to implement and hazardous to the environment. Frequently, they involve the pretreatment of ash materials, including grinding and treatment with strong chemicals or energy-intensive heating steps, which adds extra cost and complexity to the extraction process.

The TREE process combines knowledge of the matrix and form of the target elements with a mild extraction methodology at ambient temperatures via a multi-step, mild acid extraction that results in high levels of REE extraction from a low-cost waste stream.

"The use of the TREE protocol can help ensure regions with a legacy of coal and fossil energy production are part of the global transition to clean energy and play a valuable part in the global energy economy," Lopano said.

The NETL team has estimated that more than 40 million tons of WPRB coal ash are disposed of annually in on-site landfills or ponds and off-site repositories. Upon the success of the process, it is estimated that a total of 2,300 tons of REEs could be extracted per year from WPRB unused ash if TREE was widely deployed, generating $140 million to $1.4 billion per year in total value.

The team also estimates that the potential future application of the TREE process in full scale in the WPRB has the potential to supplant 11% to 16% of raw REE imports for the United States.

*Continued on page 14*

# Leaving Nothing Unused


In ongoing work at NETL, the team is exploring use of the post-TREE process byproducts for beneficial reuse to minimize the waste produced.

The researchers explained that the first step of the TREE process produces a mild-pH leachate rich in calcium and magnesium. NETL is exploring potential uses for the leachate byproduct. This leachate is being compared to materials in a federal report that concluded calcium-based salts and brines are more effective than sodium-chloride salts and brines at melting ice from pavement and staying adhered to road surfaces at a wider range of temperatures.

The NETL team noted those findings highlight the potential to use the calcium leachate from the TREE process as a new de-icing and anti-icing product, which could be developed, tested and sold to help offset REE extraction costs.

Researchers are also exploring the option that this TREE leachate can be used as an additive to enhance the effectiveness of carbon dioxide (CO2) geologic storage. The storage of captured CO2 in saline reservoirs deep within the subsurface is a major component in the nation's efforts to lower atmospheric emissions of greenhouse gas.

NETL researchers stated that the TREE leachate can be mixed with CO2 to form a denser carbonic liquid before it is injected into the saline reservoir. The technique could help speed up CO2 immobilization and significantly reduce the buoyancy force driving CO2 migration toward the surface.

Uses for the post-TREE extraction ash residuals are also being explored for a variety of re-use opportunities such as cement/concrete additives or feedstock for sorbent synthesis.

"The core of our team's research at NETL is built upon characterizing how metals are bound in materials and developing thoughtful extraction methods to minimize waste and environmental impacts," said Lopano, who has received several professional honors, including the 2020 U.S. Secretary of Energy's Excellence Award for her leadership in innovative research and development efforts to recover REEs and critical minerals from fly ash, acid mine drainage and other waste streams.

"The opportunity before us is to find productive uses for everything created through the extraction process to cover a broad spectrum of needs for the American people," Lopano said.

Development of the TREE process has been supported by the NETL Research & Innovation Center Critical Minerals field work proposal project run through the U.S. Department of Energy's (DOE) Office of Fossil Energy and Carbon Management.

The upscaling of the TREE process to a small pilot has been supported by the DOE Technology Commercialization Fund, which was created to advance the commercialization of promising energy technologies and strengthen partnerships among DOE's national laboratories, private-sector companies and academia to deploy these technologies to the marketplace.

NETL has partnered with researchers at the University of Wyoming School of Energy Resources and Energy Capital Economic Development, the nonprofit that operates the Wyoming Innovation Center, to extract REE materials from the ash of WPRB coals. ☰

# DOE-Developed Rare Earth Element Detection System Holds Potential to Revitalize Historic Energy Communities

**By Conor Griffith**

America's coal mining communities, which have helped build the nation's industries and keep the lights on, have faced challenges as a result of the rapidly changing energy landscape. However, these communities may now see an economic resurgence due to the growing demand for rare earth elements (REEs) and critical minerals (CMs), which has led to the development of a new technology by DOE to find REEs in coal-related materials.

The new device, a prototype field-portable laser-induced breakdown spectroscopy (LIBS) and Raman spectroscopy instrument, is housed in a backpack and integrated with a handheld sensor. Researchers at Los Alamos National Laboratory (LANL) developed, assembled, and tested the prototype as the culmination of a multiyear, $1 million project funded and administered by NETL.

The field portable unit could provide an easy-to-use method to determine the concentration of REEs and CMs in legacy mining sites, for example, and is capable of simultaneous chemical and mineralogical analysis of REEs in coal-related materials in the field.

"This system is compact and portable and provides a means of performing spectroscopic analyses of coal-related materials to determine the concentration of REEs and CMs in the material quickly and easily in the field, rather than waiting for samples to be delivered to an analytical facility for tests to be performed and results returned," said NETL's Brett Hakey, a federal project manager.

"This means reduced risk and expenses for potential users of the system that could remediate legacy coal related materials, while expanding the domestic supply of increasing vital critical minerals and materials."

The backpack analysis system could prove effective in helping to meet the rising global demand for REEs and CMs, which is expected to increase by 400-600% over the next several decades. In particular, demand for key magnet materials needed for decarbonization efforts, such as neodymium and praseodymium, is estimated to increase by more than 290% by 2050, relative to 2020 demand according to DOE. The Department also estimates that demand for dysprosium is projected to increase by approximately 590% over the same time period.

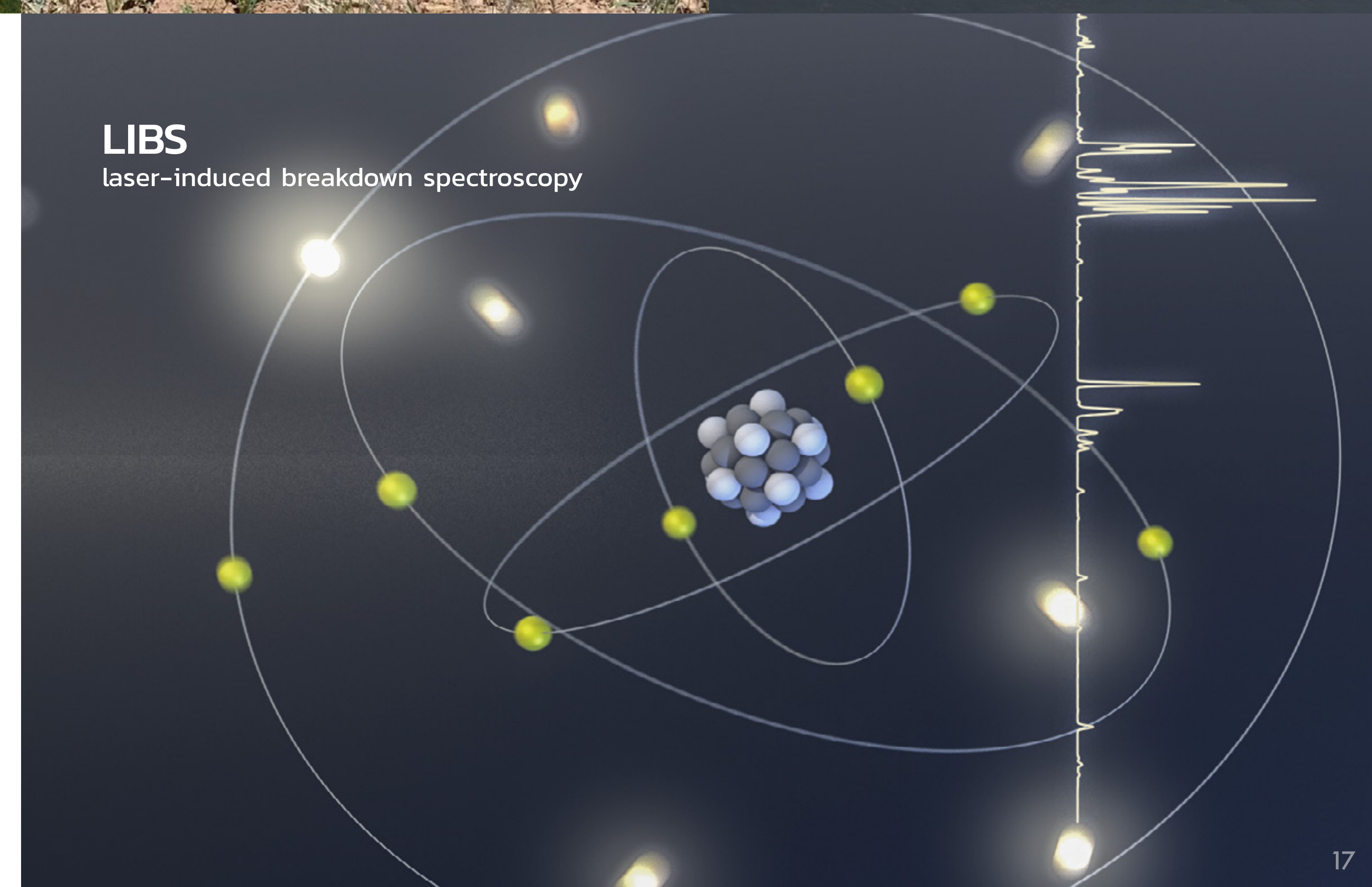
Currently, most REEs and CMs are produced and refined offshore and imported to the United States in raw form or, most often, as components already integrated into end-use products. The creation of a reliable, domestic supply of REEs and CMs is needed to ensure U.S. economic, energy, and national security.

These resources are also crucial for the ongoing push to decarbonize the country's power sector and economy at large, as the technologies needed to realize these goals cannot be manufactured without large quantities of REEs and CMs.

"These minerals are vital in the construction of clean energy technologies, including generators in wind turbines and electric vehicle motors," Hakey said.

*Continued on page 18*

**LIBS** involves ablating or removing the surface of a sample with a focused laser and generating a plasma. The chemical composition of the sample is determined by analyzing the specific wavelengths of light emitted from atoms and ions in the plasma.

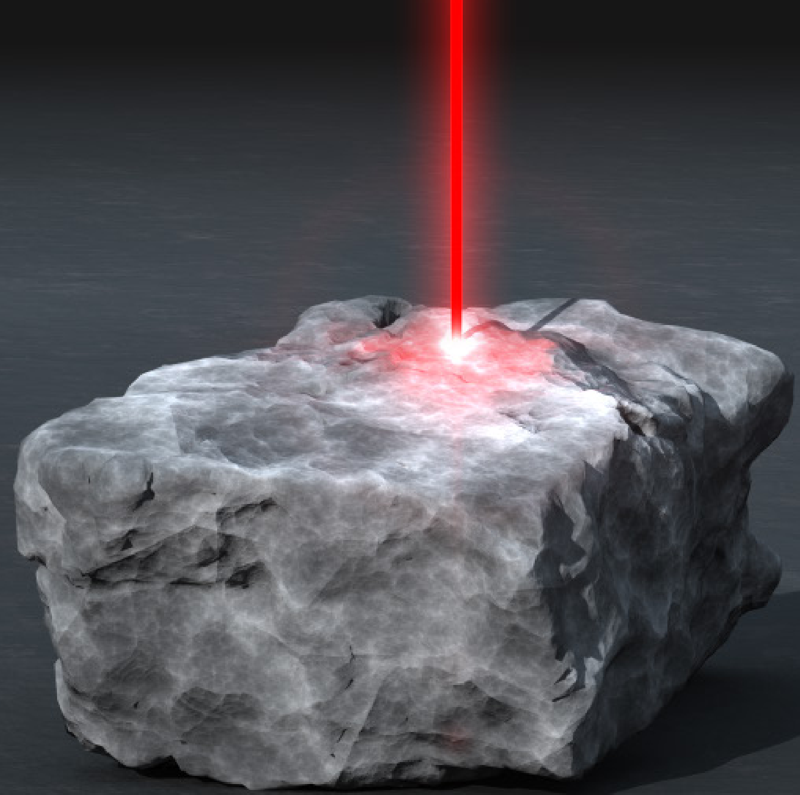


"They are also needed to manufacture defense systems, medical equipment, modern electronics and a host of other consumer goods. This new system developed by LANL has the potential to be a game-changer in the nation's efforts to develop a robust onshore supply of these materials to meet growing demand."

The LANL team leveraged its research in LIBS combined with Raman spectroscopy to develop the prototype. The integrated LIBS and Raman system was originally developed in collaboration with NASA for use on Mars and developed into a field portable system calibrated, for this project, specifically to detect REEs. NETL oversight led to applying the technology in a new direction — developing new uses for an old fuel source.

LIBS involves ablating or removing the surface of a sample with a focused laser and generating a plasma. The chemical composition of the sample is determined by analyzing the specific wavelengths of light emitted from atoms and ions in the plasma. Raman spectroscopy involves irradiating a sample with a laser such that the chemical constituents in the sample vibrate at specific frequencies, which allows for the identification of REE-mineralogical composition. Knowing the mineralogy of the REE-containing materials helps to identify the means by which the REEs can be extracted and separated from a potential feedstock material.

This integrated LIBS and Raman instrument enables the assessment of the REE chemistry and mineralogy in a single field instrument without the need for sample preparation, allowing operators to rapidly determine both concentration and composition in mere seconds and saving time and money prospecting for resources that contain high REE concentrations in forms that are easily extractable.



## Raman
### spectroscopy

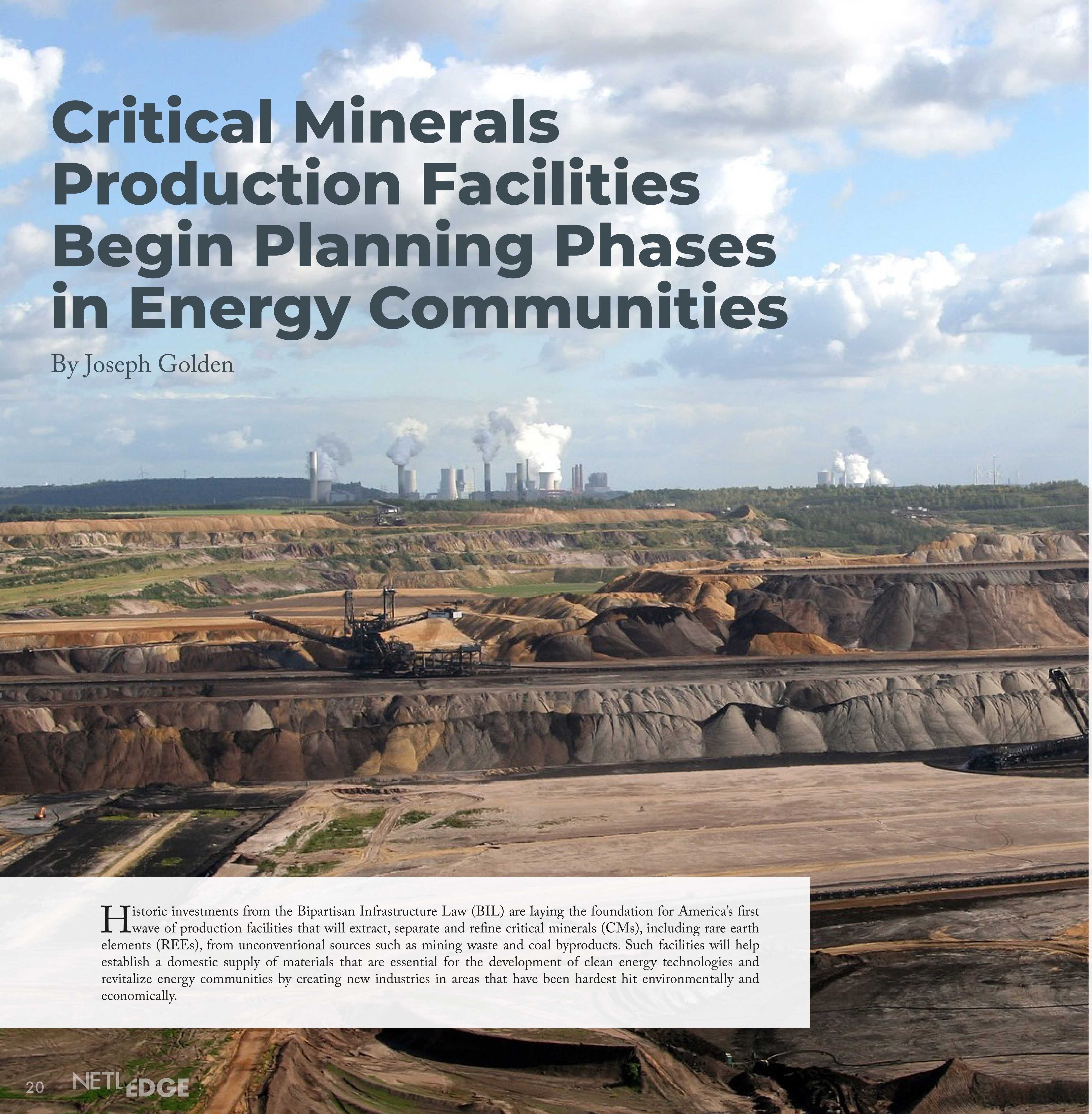
Raman spectroscopy involves irradiating a sample with a laser such that the chemical constituents in the sample vibrate at specific frequencies, which allows for the identification of REE-mineralogical composition.

The technology was tested by analyzing the concentration and mineralogy of REEs in a variety of coal-related materials from deposits in New Mexico, including rock and soil found adjacent to coal seams. It is expected that the technology could also be used to analyze the concentration and mineralogy of REEs in other solid coal refuse materials. With further research and modification, the technology could be expanded to identify a wider swath of critical minerals, not just the REEs.

"Mining communities across the United States have large quantities of coal wastes and byproducts. These materials can contain potentially hazardous constituents and, if not remediated, can contribute to serious environmental problems," Hakey said. "Working with partners at LANL, NETL has helped to advance a technology that could reduce environmental hazards by using mining byproducts as a feedstock to extract REEs and CMs."

In addition, developing new uses for coal byproducts — such as using them as source materials for REEs — could drive economic development in coal communities that have suffered through economic downturns.

"That's especially important to ensure no communities are left behind as the nation undergoes a transformational shift to clean energy," Hakey said.



# Critical Minerals Production Facilities Begin Planning Phases in Energy Communities

By Joseph Golden

Historic investments from the Bipartisan Infrastructure Law (BIL) are laying the foundation for America's first wave of production facilities that will extract, separate and refine critical minerals (CMs), including rare earth elements (REEs), from unconventional sources such as mining waste and coal byproducts. Such facilities will help establish a domestic supply of materials that are essential for the development of clean energy technologies and revitalize energy communities by creating new industries in areas that have been hardest hit environmentally and economically.

*"Research — performed by NETL and others — has shown that there are likely enough unconventional supplies of REEs in the U.S. to satisfy demands for consumer and clean energy technologies,"*

explained NETL's Jessica Mullen, technology manager for the Lab's Critical Minerals and Materials program.

*"However, facilities must be built for domestic production and refining."*

*Continued on page 22*

In recent years, DOE's Office of Fossil Energy and Carbon Management (FECM) and NETL have invested more than $41 million in external projects that support resource identification and recovery of REEs and other CMs and materials in traditional fossil fuel-producing communities across the country.

This includes $16 million in BIL funding to support projects in North Dakota and West Virginia for the development of a first-of-a-kind REE and CM extraction and separation refinery. In the first of these two projects, the University of North Dakota is completing a study to recover and refine REEs and CMs from North Dakota lignite mine wastes. The project aims to advance technologies that can enable a cost-competitive, environmentally sensitive process to produce REEs and CMs from domestic coal wastes.

In the second project, West Virginia University is working on a study for producing REEs and CMs using acid mine drainage (AMD) and mineral tailings as feedstocks with at-source pollution treatment. Intermediate products will be processed to high-purity oxides, salts or metals depending on specific market needs.

**"These two projects are not only important to the development of much-needed domestic REE processing facilities, but they are also important to the communities in which they may be constructed."**

*– Jessica Mullen*

**"North Dakota and West Virginia have a long history of energy production from coal. As the nation transitions to a clean energy economy, it's important to support technologies that have the potential to create new industries and jobs to replace those lost and to remediate the environmental and societal effects that years of coal production have taken on the energy communities."**

*– Jessica Mullen*

FECM and NETL have also recently announced that up to an additional $32 million of BIL funding will be awarded to new projects that will help build facilities to produce REEs and other CMs and materials from domestic coal-based resources.

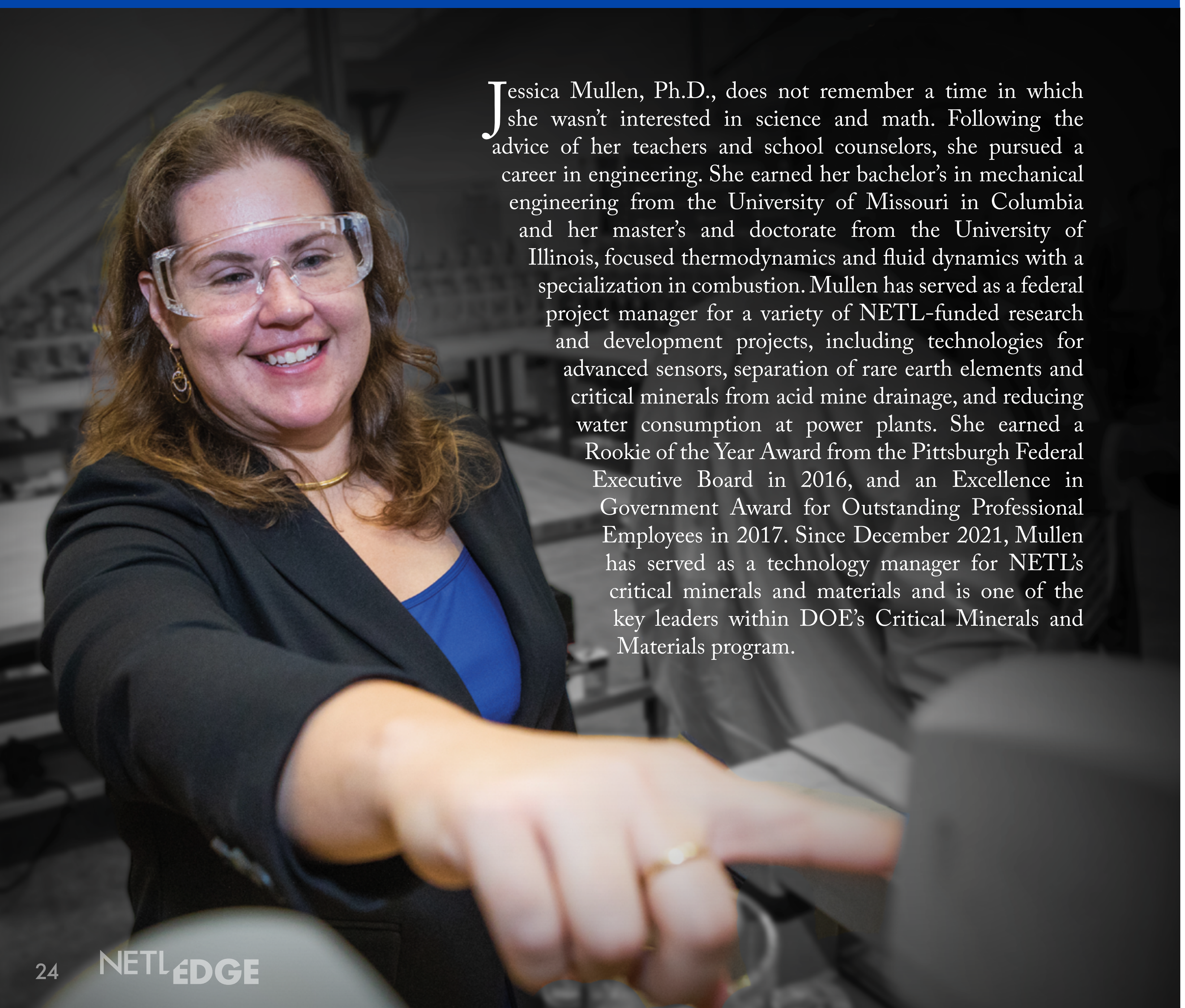
Specifically, this funding will support front-end engineering and design studies that will establish and define technical requirements focused on project scope, schedule and costs and reduce risk during the potential construction and operation of the future facilities.

These potential facilities will also help to create healthier environments for local communities by using abundant national sources of coal and coal byproducts to extract, separate and refine REEs and other CMs and materials. These unconventional resources include more than 250 billion tons of coal reserves, over 4 billion tons of waste coal and about 2 billion tons of coal ash at various sites across the country. The existing volume of AMD in streams across the nation is difficult to estimate because not all sources are known or well-characterized, but a 2018 paper by WVU researchers notes that more than 20,000 kilometers of U.S. streams are estimated to be affected by AMD.

"The United States currently imports greater than 80% of its rare earth elements from non-domestic suppliers," Mullen said. "Reliance on foreign sources makes the U.S. vulnerable to supply chain disruptions. But REEs naturally occur all around us, including in our domestic coal and coal wastes. These funding opportunities will help industry tap this unconventional resource to help build a domestic supply chain critical to the U.S. economy, clean energy and national security. Using coal wastes as REE-containing feedstocks has the additional benefit of environmental remediation of a material previously considered a burden."

# Mission Critical

## A Conversation with Critical Minerals and Materials Expert Jessica Mullen, Ph.D.



Jessica Mullen, Ph.D., does not remember a time in which she wasn't interested in science and math. Following the advice of her teachers and school counselors, she pursued a career in engineering. She earned her bachelor's in mechanical engineering from the University of Missouri in Columbia and her master's and doctorate from the University of Illinois, focused thermodynamics and fluid dynamics with a specialization in combustion. Mullen has served as a federal project manager for a variety of NETL-funded research and development projects, including technologies for advanced sensors, separation of rare earth elements and critical minerals from acid mine drainage, and reducing water consumption at power plants. She earned a Rookie of the Year Award from the Pittsburgh Federal Executive Board in 2016, and an Excellence in Government Award for Outstanding Professional Employees in 2017. Since December 2021, Mullen has served as a technology manager for NETL's critical minerals and materials and is one of the key leaders within DOE's Critical Minerals and Materials program.

> **"I am optimistic about the future of critical minerals and materials...I believe NETL and DOE are poised to contribute to this development due to our focus on unconventional and secondary resources. It will take contributions from across the government, not just DOE, to make a sustainable and secure domestic supply chain."**

### What is most exciting to you in your current work as an NETL technology manager for critical minerals and materials?

The most exciting part to me about my current work as a technology manager in the critical minerals and materials (CMM) program is that feel like I am making a difference — a difference for the future of clean energy and national security, a difference for the environment, and a difference for the communities that have been impacted by energy development in the past and that will benefit from CMM recovery efforts and supply chain development in the present and future. Technology that uses CMM is an integral part of our daily lives. We can't go five minutes without using technology built using at least one, but maybe as many as a dozen critical minerals. It is real; it can happen. We can recover rare earth elements, which are included in the envelope term "critical minerals and materials" from unconventional and secondary sources like coal and coal byproducts such as fly ash and acid mine drainage. What we do, what we're supporting and developing, it is real, and it will make a difference and it is really exciting to be a part of that.

### How did your career path lead you to NETL?

I started at NETL as an ORISE (Oak Ridge Institute for Science and Education) doctoral fellow conducting research on sensors for measuring the composition of natural gas in real time. Along with other NETL researchers, we designed and constructed two successive generations of prototypes that were then demonstrated both on- and off-site. I then became a federal project manager working on sensors and water management projects, and my team was assigned the new, at the time, rare earth program. The rest is history.

### During your career, what have you observed to be the most significant advances in critical minerals and materials, and what contributions are you most proud of?

During my career at NETL, the single biggest advance that I've seen is the entire program. My predecessors in the technology manager role developed a new R&D program, from scratch, to test the feasibility of recovering rare earth elements from coal and coal byproducts. Being a part of the project management team that supported this research and development first-hand and watching the program grow, evolve, and expand into not just feasibility of rare earth element extraction to but to now — as one of the technology managers directing the program — full supply chain development of critical materials needed for energy and national security from fossil energy (and other unconventional) sources, is just really amazing and awesome to be a part of. I first managed projects that sourced rare earths from (coal) acid mine drainage (AMD). Being a part of that research path and seeing the projects and project partners evolve and knowing I contributed in some small way has been a proud thing to look back on. Knowing that when (not if — when) AMD and other coal waste products used as feedstock sources are accepted, demonstrated pathways to CMM recovery that our program has developed while mitigating environmental burdens, and knowing I was a part of it that will be a proud moment for me.

*Continued on page 26*

**For more than 14 years, you've been a volunteer for NETL-sponsored regional Science Bowl competitions. What do you find most valuable about the activity and your experiences with Science Bowl?**

I absolutely love being able to work with students to encourage them to be more excited about math and science and all things STEM (science, technology, engineering, and math). I love being able to work with and all ages of people to encourage STEM. DOE's National Science Bowl® is such an exciting, dynamic, and involved way we, as working professionals, can engage with students and their parents and teachers to support their love of math and science. I love that these students have an opportunity to show off their brains in an athletic competition of the mind. And I get to be a part of that; how exciting! Since 2010, I've helped support regional Science Bowl events, and since the pandemic, when the world went to nearly everything virtual, I've been able to help out with regionals across the country. Last year I was even able to help the U.S. territory of Puerto Rico with their science bowl. I've also been able to help with National Science Bowl finals in Washington, D.C. It has been really exciting seeing the best brain athletes compete together in a science and math competition like no other. I only hope I inspire and encourage them half as much as they inspire and encourage me. They're our future; I'm just doing my small part to support them.

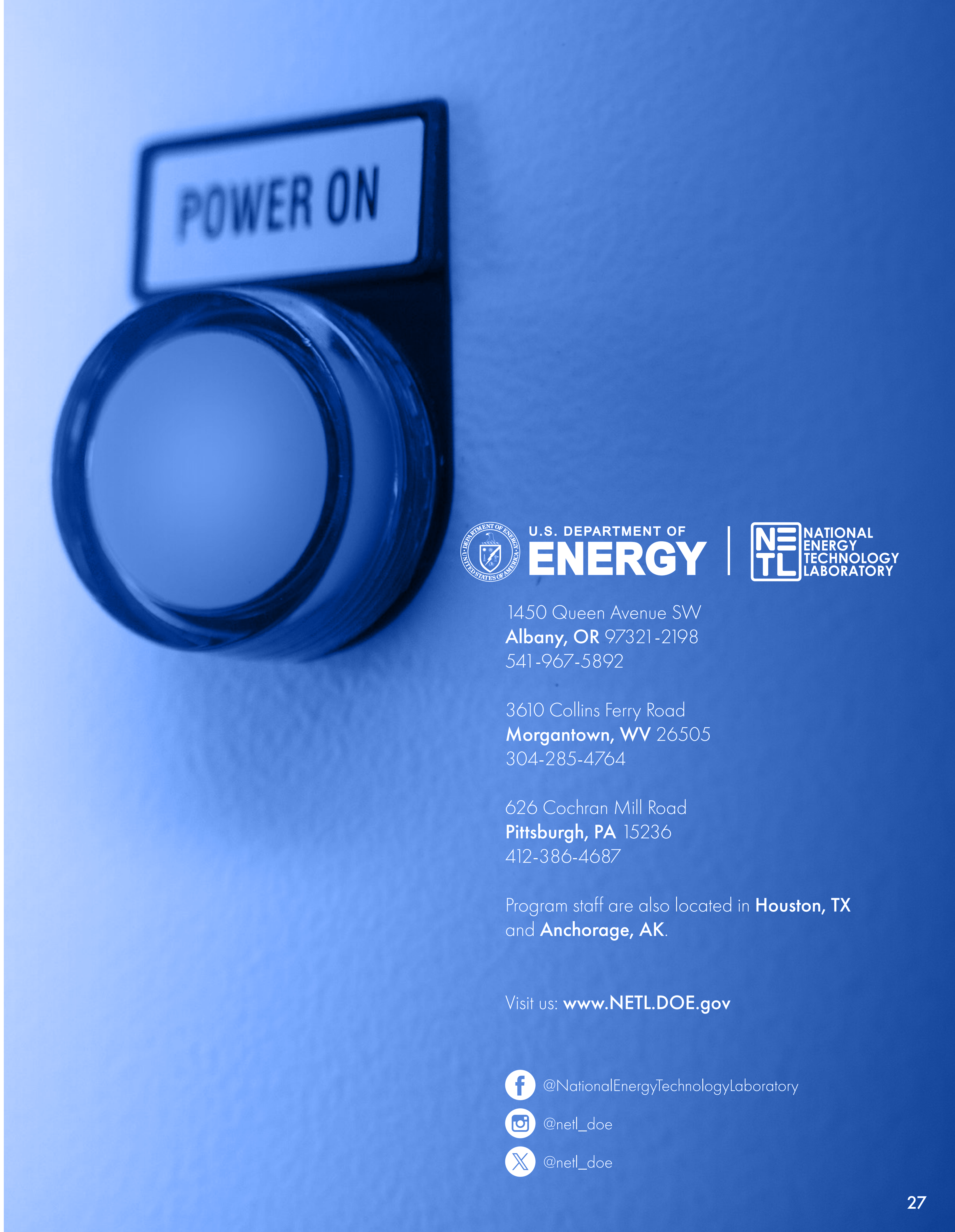
**You've also served as a mentor for the Mickey Leland Energy Fellowship program and other STEM outreach efforts. What do you find most rewarding about your experiences in mentoring younger generations and what advice would you give those who are considering careers in science or engineering?**

Being a mentor (and kind, to any person, in any field or on any topic) is a way to give back. I've been supported throughout my development and education, and it is only fair and just to give back whenever and however I can. Besides feeling it is my responsibility and privilege to participate and give back, it also feels really good to know you're helping to support and encourage the future. Even someone that is a non-traditional learner (say, a parent or a grandparent), they still represent the future when they are able to pass on what they have just learned or gotten excited about to younger generations. The best future we can imagine is when we all work together to make it better and when we all support and encourage each other to stick with challenges and opportunities in the hard times and to make the impossible possible, even if that evolution occurs via a route we didn't expect. My advice to those that are considering careers in science or engineering is to remember to have fun, experience the excitement of learning, and share that joy with others. We never stop learning even when traditional school ends. And even those who aren't pursuing majors in the typical STEM fields can have a huge impact. We need writers and journalists that are skilled at conveying information, marketing majors good at promoting and advertising new products and companies, social developers and engagers that can help us reach out into the communities and share the knowledge, and educators that will help teach and inspire future generations, just to name a few. To make a better world, it takes us all — each and every one of us has a role to play; we will get there together.

**What do you think the future of critical minerals and materials will look like?**

I am optimistic about the future of critical minerals and materials. It will be an opportunity for all of us to come together to develop the domestic critical minerals and materials supply chain from extraction from feedstock all the way through product development. I believe NETL and DOE are poised to contribute to this development due to our focus on unconventional and secondary resources. It will take contributions from across the government, not just DOE, to make a sustainable and secure domestic supply chain. I am excited to see the whole of government work together to meet this critical need and knowing that FECM's part will contribute to improving the environmental burden left behind from our country's energy history while also creating sustainable jobs and building up local communities impacted by this history. The future is bright, and it will be powered by technologies developed using critical minerals and materials recovered as a result of the RDD&D program here at NETL. That's exciting stuff right there! ≡



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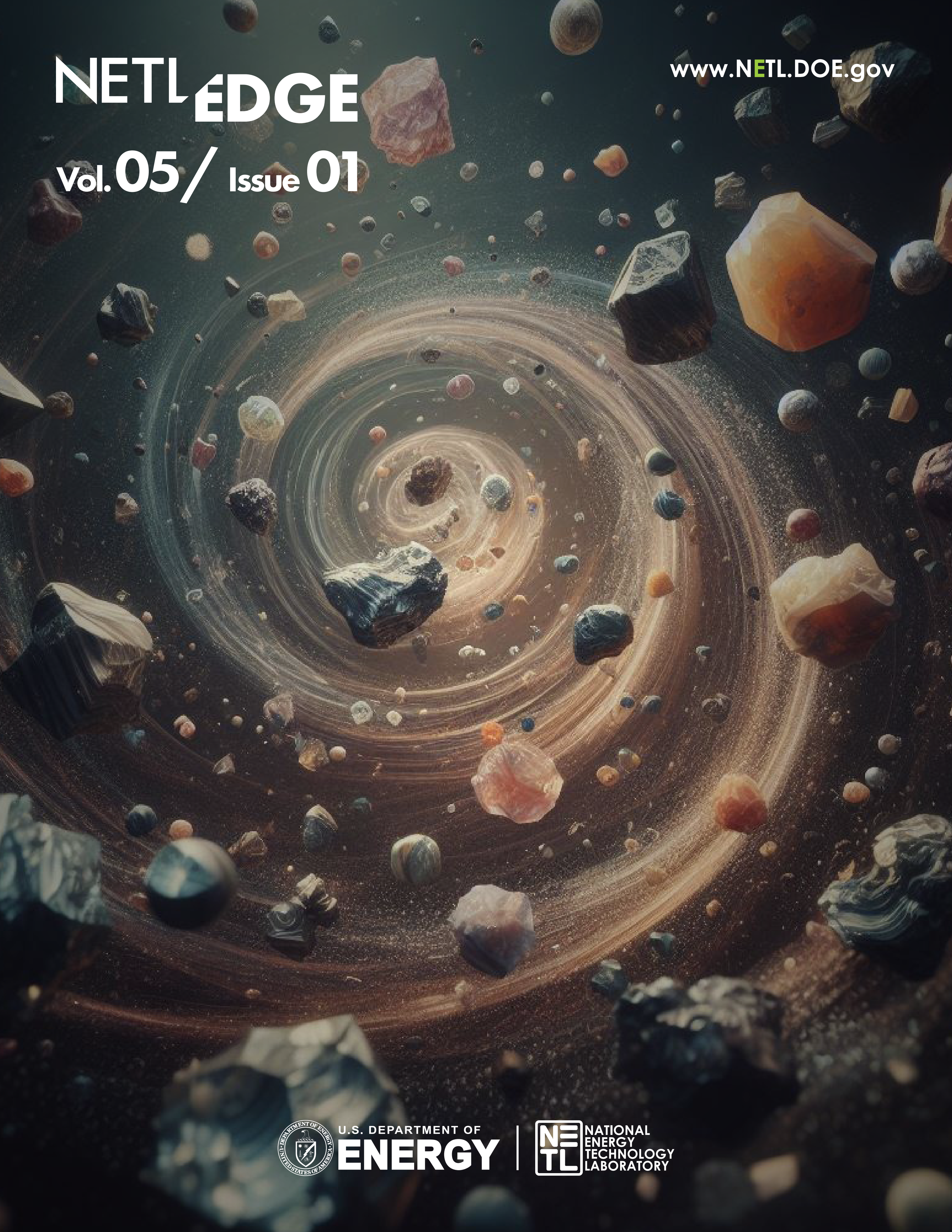

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