NETL EDGE

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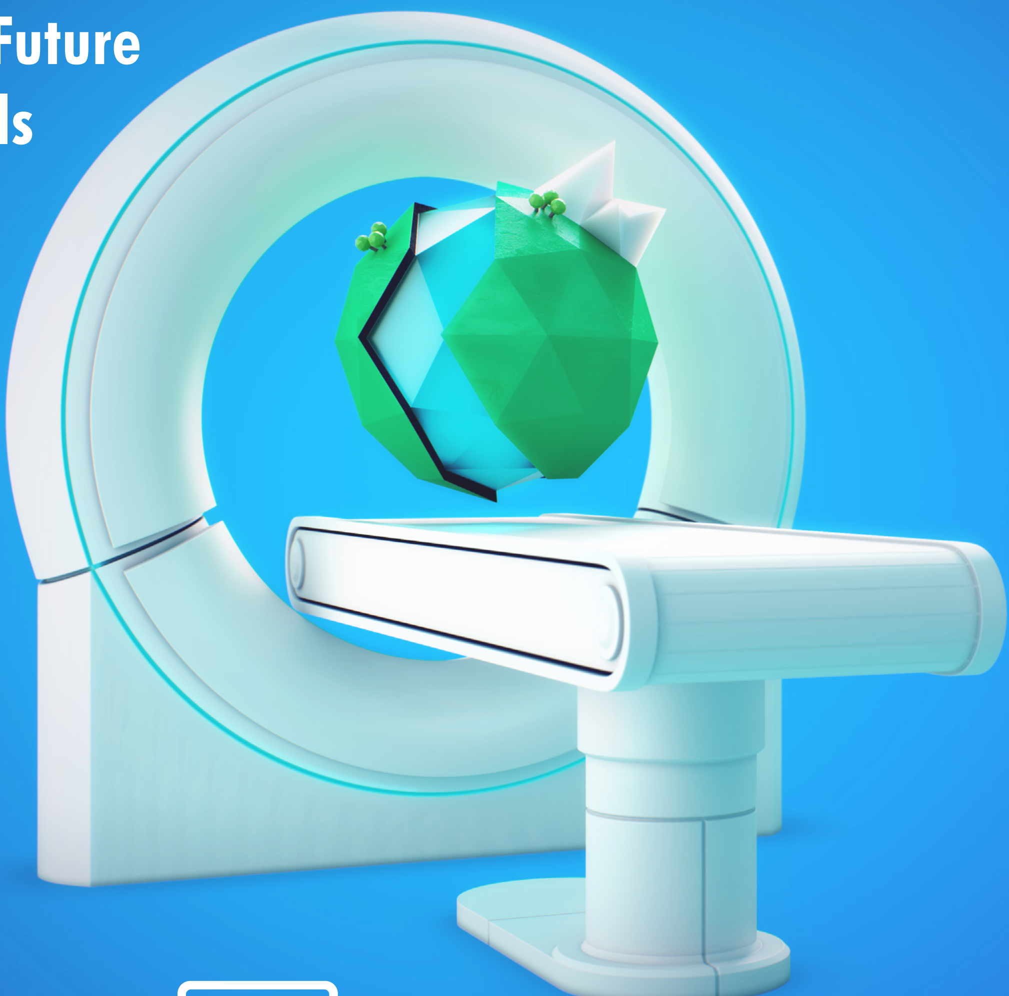
CARBON CLEANUP:

CCUS Technologies Making the Future of Fossil Fuels



NATIONAL ENERGY TECHNOLOGY LABORATORY

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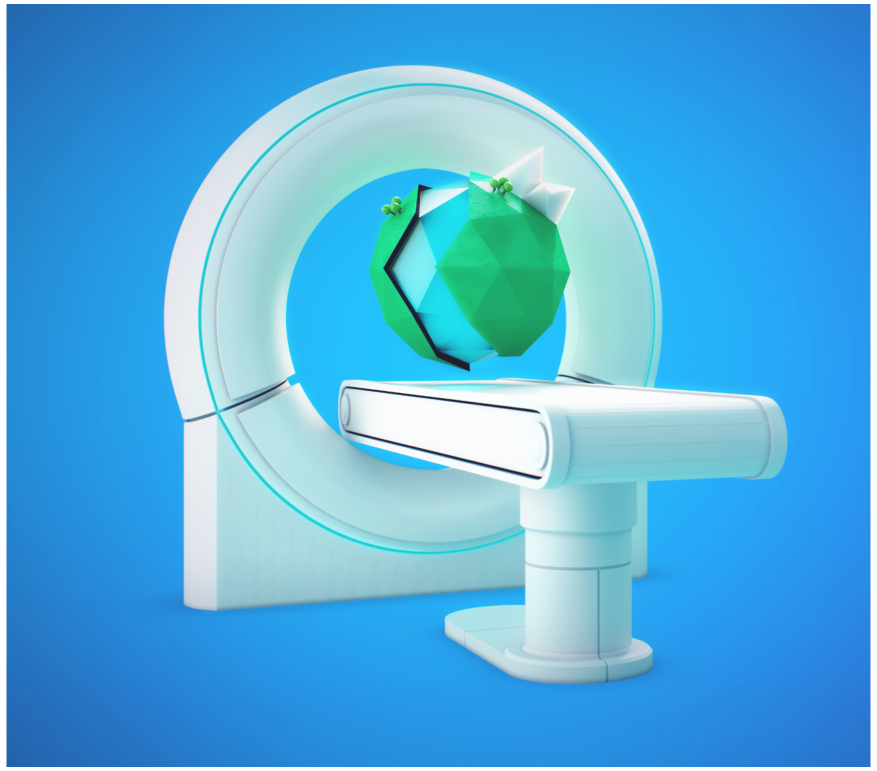
ON THE COVER



NETL's SMART Visualization Platform is shifting the way geoscientists view underground environments the same way computer tomography (CT) scans revolutionized internal medicine. This "CT for the Subsurface" uses advanced data to give a better picture of what it's like thousands of feet into the Earth.

Read more on page 10.

DIRECTOR'S MESSAGE

At the start of 2020, nations around the globe began to understand we were in the grips of a rapidly spreading pandemic. Citizens and governments worldwide prepared for the unknown and braced for potentially devastating impacts. As hospitals and healthcare professionals worked tirelessly to protect their communities and care for the sick, they were aided by an uninterrupted supply of power. As medical researchers work to understand the virus and develop vaccines and therapeutics, they depend on abundant, reliable energy.

We cannot overstate the contributions of all those on the frontlines of combatting the COVID-19 pandemic. We must also acknowledge the vital need for reliable, affordable energy. Reliable and abundant energy allows us to overcome every challenge that we face. For researchers with the National Energy Technology Laboratory, it's clear our work has never been more important.

At NETL, our talented teams of researchers are working hard to innovate technology solutions that provide abundant energy to people around the world while stringently safeguarding our air and water. As fossil energy resources continue to supply the bulk of the world's energy needs, carbon capture, utilization and storage (CCUS) technologies remain a key technology in enabling clean energy from abundant coal, oil and natural gas resources.

In this edition of NETL Edge, we feature some of the Lab's leading-edge work and collaborations in CCUS technologies. The following pages share details on how:

- Subsurface modeling and visualization is revolutionizing our understanding of the complex geologic environment and improving resource recovery and reservoir management.
- Plastics upcycling using microwave technology can creatively repurpose old materials into fuels, other plastics and value-added chemicals, offering a potential solution to plastic waste.
- NETL's work with modular process intensification holds significant value for industrial applications and new markets for high-value products from fossil fuels.
- Coal can be used to affordably manufacture valuable products like graphene that is stronger than steel, highly conductive and can enhance the performance and service lifetimes of materials used throughout our nation's infrastructure.

Before anyone heard of COVID-19, the research community was united in a mission to combat global climate change. We are making great strides and demonstrating the power of research to overcome challenges. The pandemic may have complicated our daily endeavors, but it has not deterred our mission. In fact, it has strengthened our resolve to provide technology solutions that make people's lives better and safer, protect our environment and power our prosperity. I'm proud of our progress to date, and I'm pleased to share a selection of work in CCUS research.

Brian J. Anderson, Ph.D.
Director, NETL

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Problems Posed by Plastic

To date, about eight billion tons of plastic have been produced globally for applications ranging from home construction to medical equipment and everything in between. More than 300 million tons of plastic materials are manufactured annually worldwide. Much of this production is for single-use only, such as packaging, resulting in huge amounts of plastic waste that end up in landfills or in the oceans where it poses a significant hazard for marine life.

A potential solution put forth by NETL is plastics upcycling, which creatively repurposes old materials while maintaining some of their original characteristics, whereas recycling breaks old items down into their raw materials to be made into new products. While recycling has seen some success for glass, paper, and metal, plastics is another story. Only about five percent of plastic is recycled due to the extra processes involved that drive up costs and energy use, processes that aren't required to recycle metal or glass.

The traditional approach to recycling/upcycling involves heating a storage vessel to melt components down. Plastic isn't conducive to this method. First, there are many hybrid plastics, which must be sorted and preprocessed — polyethylene (high density and low density), polypropylene, polystyrene, PET, PVC, polycarbonates, and polymer composites are a few examples. Second, additives common in plastic products, such as ink, dyes, chlorines, and other chemicals, must be leached out before recycling. Third, products' multilayer packaging often contains metal, which must be separated and recycled separately.

Getting through these obstacles creates expenses to the point that it is cheaper to manufacture new plastics instead of upcycling — adding to the already rapidly growing landfills.

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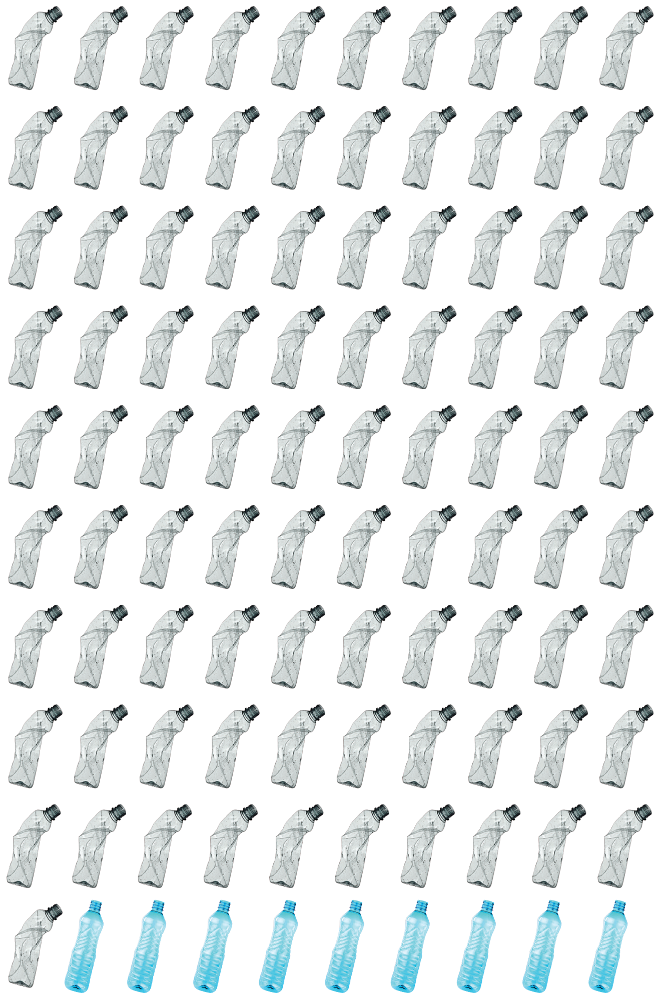


Of the plastic waste produced between 1950 and 2015, only 9 percent was recycled.

NETL's Single Stream Solution

NETL's solution to traditional chemical upcycling is through the same process carried out in kitchens and breakrooms the world over: microwave heating, albeit on a much larger scale. Microwave radiation disassembles the component polymers in plastic objects, such as water bottles, to collect their constituent building blocks for reuse. This means old plastic can be remade into fuels or used in the production of other plastic products and value-added chemicals.

NETL researchers are on the leading edge of using microwaves for synthesizing chemicals and optimizing a range of reactions, valuable for energy applications. One recent success was in demonstrating the effectiveness of microwaves for synthesizing ammonia, a primary fertilizer ingredient and a potential fuel source for electricity generation without carbon emissions. Their microwave-based approach used lower temperatures, lower pressures and less energy than what is required in the Haber-Bosch process, the prevailing method to make ammonia in bulk.

The Lab's engineers and scientists are now working on applying the same principles to the chemical upcycling of plastics. What distinguishes NETL's method from other microwave-based projects is its single-stream nature, which requires minimal sorting and provides strong incentives to reuse plastic rather than dump it.

"Most of the work done so far, both in research and start-ups using microwave technology, is focused only on one type of plastic, but we're aiming for an upcycling mixed plastic stream," NETL researcher Pranjali Muley Ph.D. explained. "This will not only reduce sorting cost, but expand recycling activities significantly. We are exploring microwaves for specialty applications such as deconstruction of polymer composites to recover fiber and upcycle the polymers."

Because the plastics themselves are being heated rather than the containers they're placed in, microwave-assisted upcycling is also more energy efficient, allowing more products to be recycled for a lower price.

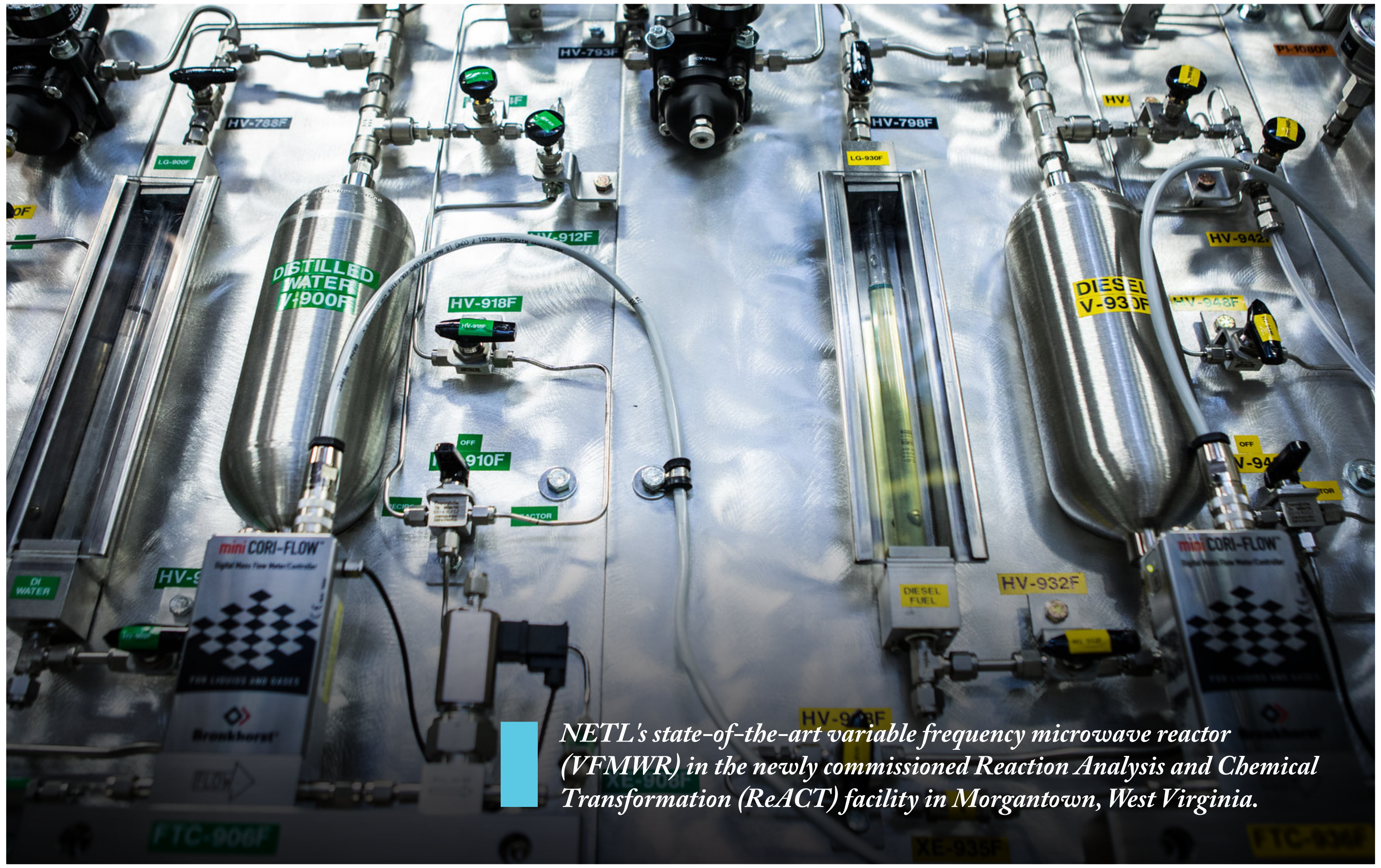
Building Up the Circular Economy

Muley expressed confidence in the capabilities of NETL's researchers, their experience, and state-of-the-art resources such as the Reaction Analysis and Chemical Transformation facility (ReACT), which houses the equipment to selectively energize chemical reactions and optimize chemical transformations through electromagnetic energy such as microwaves. In addition, Muley sees great promise in the future for large-scale deployment because of the modularity of microwave-assisted plastics upcycling process.

"The advantage of something modular is that we can put it on small sites, like a sorting facility with low energy demands," Muley said. "A microwave-based system would be low maintenance with low losses of power. Our research shows that microwave heating could be up to 30 percent more energy and cost efficient than traditional reactors."

If optimized and commercialized, NETL's innovations could lay the foundations for a circular economy regarding plastic. Because the technology is relatively small and cost efficient, it can be added on to facilities already producing plastic products. It could be deployed in a distributed fashion to make plastic upcycling available across the country and enable the use of intermittent energy resources such as wind and solar due to its power efficiency. Discarded plastic primed for re-use can be brought back and the cycle continues.

This means large, centralized recycling/upcycling plants for plastic would no longer be needed, not only lowering the transportation costs but also reducing energy use and CO_2 emissions. A circular economy for plastic products can promote responsible stewardship of the planet while ensuring the supply of products that make daily life possible can continue uninterrupted. Without viable alternatives to



NETL's state-of-the-art variable frequency microwave reactor (VFMWR) in the newly commissioned Reaction Analysis and Chemical Transformation (ReACT) facility in Morgantown, West Virginia.

plastic, such an economy may prove necessary to balance long-term sustainability and economic demand.

Progress Through Partnerships

NETL's partners in industry and academia have also recognized the energy, environmental, and economic benefits of single-stream plastics recycling through the use of microwave technologies. West Virginia University has been a long-time collaborator in developing new uses for microwave reactors and appropriate catalysts.

"By combining our assets, NETL and WVU synergized to develop microwave catalysis technologies with applications in ambient pressure ammonia synthesis and natural gas conversion to chemicals. In the process, we discovered potentially revolutionary uses for a process often taken for granted," said WVU Professor John Hu. "In working with NETL to make plastic upcycling for the production of value-added chemicals a reality, we have a chance to tackle one of the world's most daunting challenges head-on."

Professor Dorin Boldor, of Louisiana State University who has also worked with NETL, spoke of the Lab's plastics recycling potential.

"The upcycling of carbon-containing plastics waste and its conversion into carbon composites and other materials will provide great benefits to society by reducing its overall carbon footprint while maintaining a high standard of living in the United States," he said. "We are very lucky that the government of the U.S. and the Department of Energy provide resources for basic and applied research via NETL, resources from which benefit not only universities such as LSU, but the U.S. public at large through development of technologies that find their way in the economy through start-up companies that power the growth of jobs across the U.S."

NETL's microwave reaction chemistry research will have benefits to the country far beyond fossil fuels production. As the Department of Energy's fossil energy laboratory, NETL has the knowledge base and experience to bring emerging microwave technology concepts out of the laboratory in a broad range of applications from cost effective plastic recycling to direct capture of CO_2 from the air.

As NETL innovates, the Lab continues to forge new partnership opportunities for commercialization while fine tuning the technology, technology that could prove to be the driver of a new recycling industry that overcomes the obstacles of past attempts. The Lab's innovative use of microwaves has demonstrated that simple solutions to complicated problems can be feasible and that plastic can still be fantastic if approached in the right manner. ≡

CT for the Subsurface:

NETL's SMART Visualization Approach

By Martin Kinnunen

It's a comparison that NETL's Grant Bromhal, Ph.D., makes frequently to illustrate how a new approach to visualizing the subsurface will revolutionize our understanding of the complex geologic environment and improve resource recovery and reservoir management — the same way computerized tomography (CT) scans created a paradigm shift in medicine.

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> "Forty years ago, hospitals began using CT scans to obtain images of organs and tissue inside the human body. We are now developing a 'CT for the subsurface,' a tool to see inside the Earth and understand what occurs thousands of feet underground."
>
> - Grant Bromhal, senior fellow for Geological and Environmental Systems

Unlike CT scans, which combine hundreds of X-rays to produce 3D images, the Science-informed Machine Learning for Accelerating Real Time Decisions in Subsurface Applications (SMART) Initiative will rely on advanced data analysis to interpret vast amounts of data from multiple sensors and other sources to create visualizations of subsurface features and formations.

SMART's goal is to bring the subsurface to life through the development of an innovative, user-friendly and intuitive visualization platform, making subsurface insights accessible to a wider range of users and stakeholders. The initiative will also provide data-driven approaches to efficiently produce oil or natural gas and safely store CO_2 deep below the surface.

Launched in 2019 by DOE's Office of Fossil Energy, the SMART Initiative engages 15 different research organizations, including national labs and universities. The initiative will incorporate years of data and recent advances in data collection technologies that include novel wellbore-based sensors and micro- and nano-sensors to monitor the subsurface. SMART will also leverage data storage and high-performance computing capabilities to enable dramatic improvements in the visualization of key subsurface features such as faults, fracture networks and fluid flows.

The program is moving forward with specific development activities for oil and gas (OG) recovery and carbon storage (CS) — both of which are U.S. priorities to achieve energy independence while reducing atmospheric levels of CO_2 from industrial sources.

For example, SMART-OG will focus on providing information in an easy-to-understand format to improve recovery factors from unconventional wells, which will enable productive wells at lower oil prices and reduce the environmental footprint of oil and gas extraction.

Also, visualization will demonstrate for decision-makers how to best stimulate oil and gas recovery, taking advantage of the many field laboratories in which DOE has invested over the past several years. The platform could show how adjusting pressures during production can increase resource flow into the well or how adjusting the size or amount of fluid and proppant and hydraulic fracturing techniques can impact the effectiveness of stimulation activities.

SMART-CS, using robust data collected over 15 years from field operations and the Regional Carbon Sequestration Partnerships initiative, calls for an interactive platform to forecast how underground CO_2 storage reservoirs would perform under a variety of operational strategies. The tool could become especially helpful in forecasting CO_2 plume migration in response to an injection of carbon into a reservoir.

"Visualization will provide real-time answers when geologists, regulators and the public ask, 'What is the permeability and thickness of the cap rock layer above the CO_2 reservoir and is it sufficient to store CO_2 safely and permanently?" Bromhal explained.

"Likewise, the tool will help producers determine the best location to drill a new well so it can reach multiple reserves of gas or oil, which is both efficient and productive" Bromhal added.

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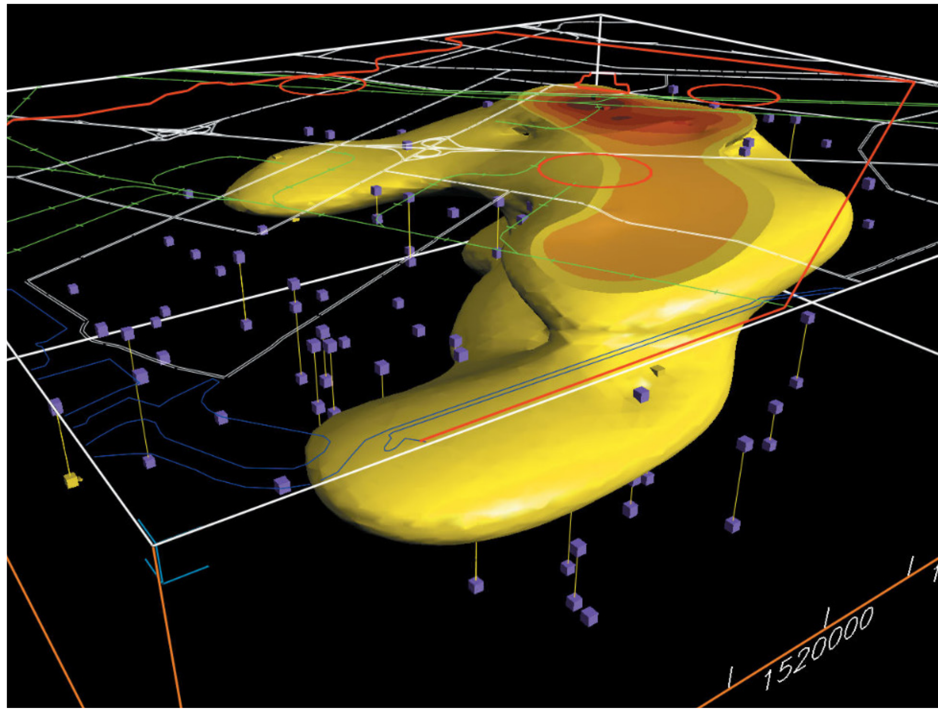
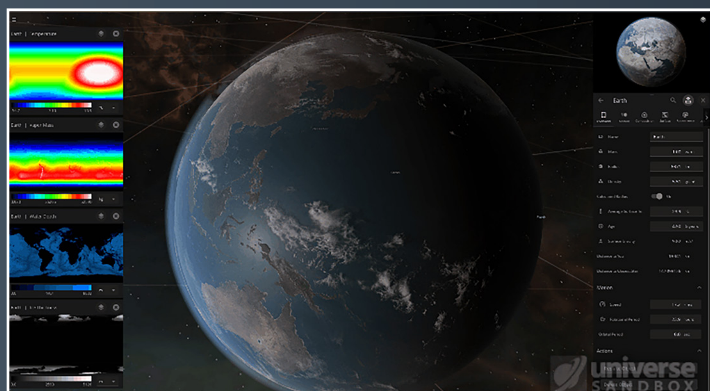


Annotated site displayed above contaminant plume and input data.

Gaming Software Plays Major Role in SMART Visualization Platform



Universe Sandbox – example of interactive educational game.

In their project proposal, the SMART team emphasized the need to build a visualization platform that's both attractive and engaging. Those elements can be infused into visualization tools using gaming software to create a dynamic experience for both subject matter experts and others with limited knowledge about subsurface operations.

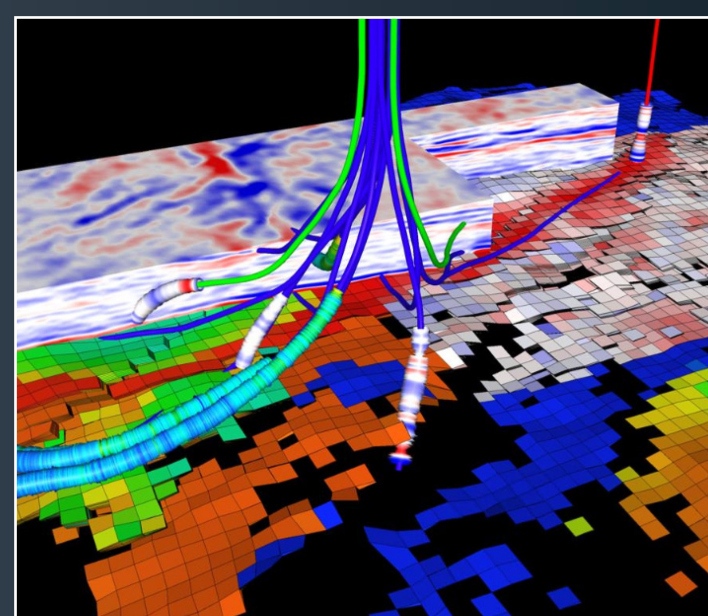
Examples abound. Bromhal pointed to an online game that allows players to complete physics-based simulations and learn how seasons change by adjusting the tilt of the Earth or watching a supernova unfold by increasing the age of a star.

SMART will use its vast volume of subsurface data and machine learning techniques to forecast what injection patterns are the most efficient in an area and how operations will change the stress or fracture network over time. This information will help predict which wells in a field are most at risk for failure and visually answer other key questions for operations.

A platform with such user interface and visualization capabilities would have other benefits. It could be used to streamline communications between operators and regulators and reduce delays in the permitting process. Such a platform also could be used to demonstrate to the public how a CO_2 storage system will behave and to help communicate risks and demonstrate safe subsurface behaviors.

Bromhal pointed out that a variety of platforms are available from industry. But most, if not all, of these platforms require expert training and experience to be implemented with any utility, or they come with an extensive licensing or purchase cost, making them inaccessible to a wider user base. Such restrictions would not be placed on the SMART platform, and the technology would be available for low or no cost.

The platform also will include a virtual learning component for use by engineers planning a subsurface project and others who need answers. "It could be used by property owners who want to 'see' what is happening deep underground and make sure their land won't be impacted by new oil and gas or carbon storage operations," Bromhal said. The user could refine the safety forecast to fit their specific conditions by altering details such as the depth of the well or the porosity of the shale deposit. ☰



A quantitative analysis of temporal and spatial well data integrated with a dynamic reservoir simulation and 4D seismic data within a multidisciplinary data fusion environment.

WANTED:

Software Developers Up for a Challenge

Technical teams of scientists and engineers spanning various research organizations, including NETL, as well as industry and university partners, are working on various components of the SMART project. However, a key piece of talent remains missing.

To fill this need, DOE and the Office of Fossil Energy will launch the SMART Visualization Platform Challenge, an opportunity for software developers and skilled innovators in similar fields to create a comprehensive visualization solution for the subsurface environment that can be readily accessed by scientists, engineers, regulators and the public, and works in unison with both traditional data and data output from new machine learning workflows.

The tool to be developed should help users visually answer important subsurface questions about reservoir behavior, reservoir composition, injection patterns, uncertainty in measurements and other critical issues. It's important work that will help experts and non-experts better understand the subsurface and make better decisions to develop oil and gas resources and protect the environment.

This challenge will take place in two phases, both of which NETL will manage.

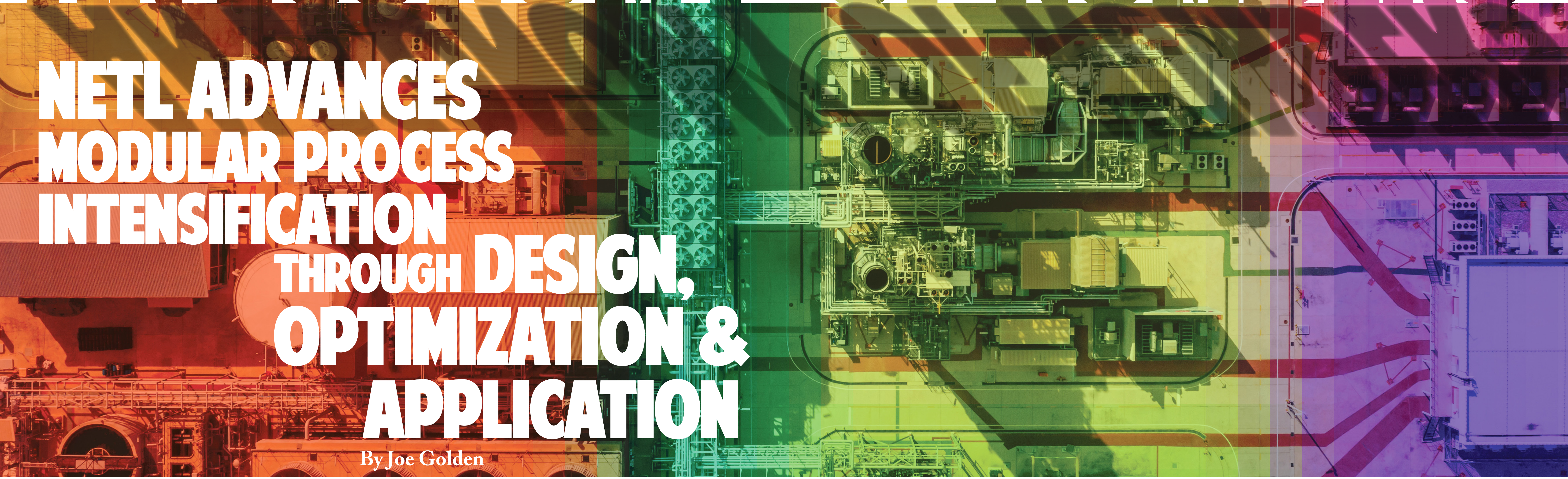
Competitors will register for phase 1 and work over a four- to five-month period to design a prototype visualization system that meets defined challenges subsurface researchers face. The first phase is expected to award up to five prizes and up to a total of $600,000 split among the winners.

Winners selected from phase 1 will work with SMART Initiative scientists and engineers over a 10-month collaborative effort to fully develop their concepts in phase 2. The winner of phase 2 will receive the Grand Prize (worth up to $900,000) and may be granted the opportunity to work on future software development projects for the SMART Initiative.

The challenge will be formally announced at netl.doe.gov, energy.gov/fe and Challenge.gov.

Watch for announcements in computer science, gaming and visualization magazines and blogs.

AN ECONOMY OF NUMBERS



NETL ADVANCES MODULAR PROCESS INTENSIFICATION THROUGH DESIGN, OPTIMIZATION & APPLICATION

By Joe Golden

Throughout the history of chemical engineering, the paradigm of "economy of scale" has dominated design of chemical and power generation processes. Prevailing wisdom asserts that larger plants will provide the most significant cost advantages through increased production. However, leading researchers around the world, including those that make up the creative and visionary NETL workforce, are asking "is bigger always better?" Increasingly, the answer is that smaller, more flexible modular units can be manufactured in greater quantities to drive down costs — an economy of numbers, rather than of scale. Furthermore, modular units could be designed to integrate multiple tasks, intensifying their processes.

NETL is at the forefront of this new approach, which is referred to as modular process intensification, as it provides cutting-edge design and optimization technology through the Institute for the Design of Advanced Energy Systems Integrated Platform (IDAES) and practical application to carbon conversion through its microwave enhanced chemistry and catalysis research at the Lab's groundbreaking ReACT (Reaction Analysis and Chemical Transformation) facility. This NETL work holds significant value for industrial applications and specifically carbon conversion industries, as it could open the door to new markets for high-value products for fossil fuels.

IDAES, the Next-Generation Multi-Scale Modeling and Optimization Framework

Process intensification involves integrating tasks that would normally be contained in different pieces of equipment or changing the way something occurs so that you have a greater level of intensity (of energy, mixing or reaction) in a smaller, more efficient space. A classic example of process intensification is the methyl acetate process developed by Eastman Chemical, in which five process that had been contained in five different vessels were redesigned to all take place inside of one distillation column. Such an advancement took both brilliant insight and some degree of luck.

At the time the process was invented, there was no way to systematically investigate options for such a process intensification. A framework didn't yet exist for multi-scale modeling and optimization of next-generation systems. Today, industry can leverage advanced computational tools such as IDAES to explore new concepts in ways that have never been possible before.

In general, when developing models for different types of intensified processes, it is difficult to represent them in a traditional commercial process simulators because their model libraries were designed for existing, traditional systems rather than the novel processes that may come to define the energy and chemical producing systems of the future. This is where IDAES bridges the gap.

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Formed in 2016, IDAES helps companies, technology developers and researchers to model, design and optimize complex systems, potentially resulting in tens of billions of dollars in savings. As an equation-oriented, optimization-based integrated process modeling platform, IDAES enables rigorous analysis of multi-scale, dynamic processes and operating scenarios to improve efficiency of existing systems and develop next-generation energy systems. IDAES has thousands of downloads and an active, growing global user community from multiple industries.

IDAES
Institute for the Design of Advanced Energy Systems

- Leverages the computational advances of process systems engineering research and integrates the multiple types of energy analysis typically conducted by disparate groups.
- Develops and demonstrates next-generation computational tools to enable the rapid design & optimization of advanced energy systems.
- Applies these tools to the development of new, advanced energy systems.
- Develops highly innovative processes that go beyond current equipment & process constraints.

Exploring new concepts

Improving efficiency, reliability, and life expectancy of existing technology

Accelerating innovation

The National Energy Technology Laboratory's IDAES seeks to be the premier resource for the identification, synthesis, optimization, and analysis of innovative advanced energy systems at scales ranging from process to system to market. The Institute supports the transformation of the national energy landscape to meet the U.S. Department of Energy's three enduring strategic objectives

Economic Competitiveness

Energy Security

Environmental Responsibility

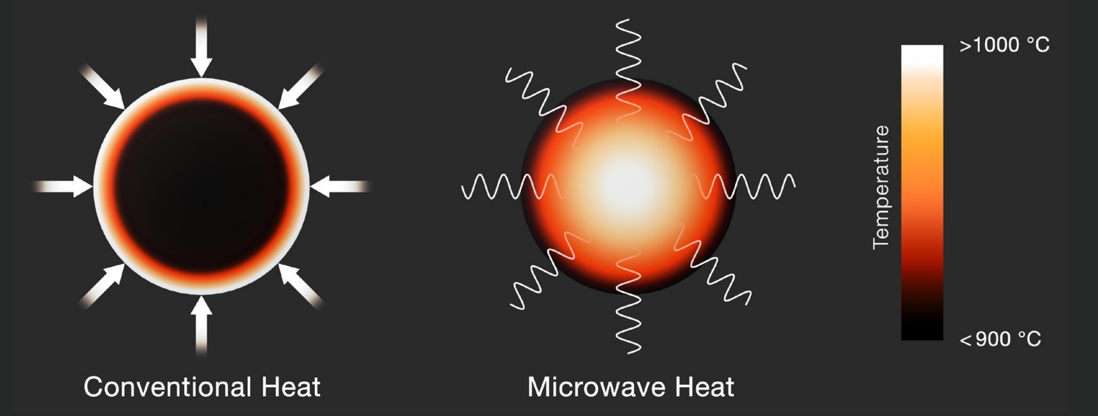
"When designing processes that are radically different than current experience, you need tools to help explore the design space," NETL Senior Fellow and Technical Director of IDAES David Miller, Ph.D., said. "IDAES enables users to build models of novel equipment and optimize the overall system."

A Stakeholder Advisory Board was assembled to ensure that the work done by IDAES remains aligned with key industry needs. Regular interaction ensures that stakeholders remain well informed of the program and its progress. This direct interaction also allows stakeholders to provide advice to the program, maximizing value to industry.

Industry has already begun to leverage the power of IDAES. For example, Clas A. Jacobson, Ph.D., senior fellow, systems engineering for Carrier Corporation said, "I believe that the IDAES program is innovative and is already having impact on industry to achieve differentiated levels of performance of systems and to significantly increase the accessibility of models and being able to use the models across the engineering talent to make design decisions."

Researchers working within IDAES have developed capabilities that can help analyze the tradeoffs among design alternatives and identify novel equipment configurations. Supporting process intensification is just a portion of what IDAES provides industry. As more companies use IDAES technologies they are seeing the full potential of services available.

For example, Ben Weinstein, Section Head Product and Process Systems, Corporate Function Research and Development for Procter & Gamble said, "Beyond energy systems, this platform will enable the process industries to solve problems that are not possible with existing modeling and optimization software and create an open source modeling and optimization community that will harness the intellectual power of the academic and industrial communities to develop innovative solutions."



A microwave reactor allows multiple microwave frequencies to be used in the same process to create more refined products, like ammonia, from a hydrocarbon feedstock like methane.

Microwave Research and Efficient Carbon Conversion Methods

Modular process intensification can also focus on improving chemical reaction methods as with NETL's inhouse research into microwave-assisted catalysis.

In NETL's ReACT Facility, researchers use the lab's unique reactor systems to unleash the power of microwaves to convert fuels like coal, oil and natural gas into marketable fuels, chemicals and products. In addition to providing higher yields with lower temperatures and less energy, this work is also advancing understanding of the science behind the reactions through state-of-the-art bench-scale facilities with an eye toward scalable and economically viable systems.

"Traditional fuel conversion processes rely on thermal heating, which works from the outside in," said Dushyant Shekhawat, Ph.D., who leads NETL's Reaction Engineering team. "However, microwaves offer a process intensification approach, operating on a molecular level to allow rapid, selective heating."

Cutting-edge facilities at NETL are aiding in this development every day. In addition to employing fixed-frequency reactors, the Lab has developed a one-of-a-kind variable frequency microwave reactor that can operate from 2 to 8 GHz.

"This unit will provide NETL with the most comprehensive look at the electromagnetic characterization of a wide range of materials for a series of chemical reactions," said Shekhawat.

NETL researchers have already achieved success using microwaves for fuel conversion processes. For example, in a project with the Advanced Research Projects Agency-Energy (ARPA-E), NETL showed that microwave irradiation could achieve significantly higher ammonia yields at lower temperatures (300 degrees Celsius) and ambient pressures using metal-supported catalyst systems. Ammonia is one of the most widely used chemicals in the world, especially in the fertilizer market, and developing a more efficient system could save considerable water and energy resources.

NETL is also working on a project sponsored by the Rapid Advancement in Process Intensification Deployment (RAPID) Manufacturing Institute. In this effort, NETL and partners are developing a microwave-assisted catalytic process to produce value-added chemicals from natural gas.

William J. Grieco, Ph.D., CEO of RAPID Manufacturing Institute explained that using microwave catalysis has the potential increase product yields using less energy and requiring less capital.

"RAPID has been pleased to fund and work with this project team, led by West Virginia University and including Shell, University of Pittsburgh, and NETL, to explore novel microwave heating for direct conversion of natural gas to chemicals," Grieco said. "The NETL team and the ReACT facility, have been critical to the success of the project. Based on results so far, we're optimistic that the microwave approach can be used for many applications, including large-scale natural gas conversion plants."

NETL's work in microwave-assisted conversion science is ongoing, and each new discovery is pushing the boundaries of process intensification for carbon conversion applications, which has vast potential to change how the nation uses its abundant and affordable fossil fuels to produce a wealth of value-added chemicals that will continue to enrich the lives of Americans.

Whether designing and optimizing future processes to take full advantage of process intensification or developing more efficient reaction chemistry, NETL research is paving the way for both the energy systems and chemical processing plants of the future.

POWER

Beyond Electricity

Coal-based Graphene's Promises

From new construction materials for the roads and bridges of tomorrow to advanced sensing materials used in modern medical technology, the world-class scientists of NETL are hard at work innovating solutions to real-world problems using state-of-the-art facilities and the tried and true resource that powered and built the United States: coal.

Harnessing Advanced Materials

With ever-increasing advances in technologies come new ways of addressing infrastructure such as roads, bridges, and buildings with advanced materials. One such material is graphene. An incredibly versatile material, graphene is one single atomic layer of carbon thick, stronger than steel and possesses higher electrical and thermal conductivity than copper. It can be added to traditional materials to enhance their performance and service lifetimes.

Graphene is currently being evaluated for anti-corrosion coatings and paints, efficient sensors, faster electronics, flexible displays, efficient solar panels, faster DNA sequencing, drug delivery, and more. The list of potential applications for graphene is seemingly infinite.

Despite its amazing properties, graphene is still not widely commercialized, in large part due to its historically high cost and limited supply. However, in recent years, an influx of graphene producers have brought new manufacturing methods to market, which has helped to bring the prices down from $1-10 M/ton 5-15 years ago to the current pricing of $300 K/ton.

While this may still seem cost prohibitive, graphene is usually only used at fractions of a weight percent in products which means it costs approximately the same as other high-tech materials. As a result, a rush of new materials are starting to emerge on the market that are leveraging the drop in graphene prices to make innovative products.

Despite the recent advances in reducing graphene costs, there is still a need to improve both pricing and material quality in this market. To address these issues, NETL launched a multi-year research effort that collaborates with industry, other national laboratories, and university labs to look at using domestic coal as a feedstock for making graphene instead of the graphite and light gases that are typically used.

Coal is 15-30 times cheaper than the graphite feedstocks currently used to mass produce graphene and NETL's research indicates coal feedstocks can easily produce graphene that is as good of quality, or better, than what is currently sold on the market. All of these factors will contribute to additional price reductions for graphene, as well as more products reaching the market.

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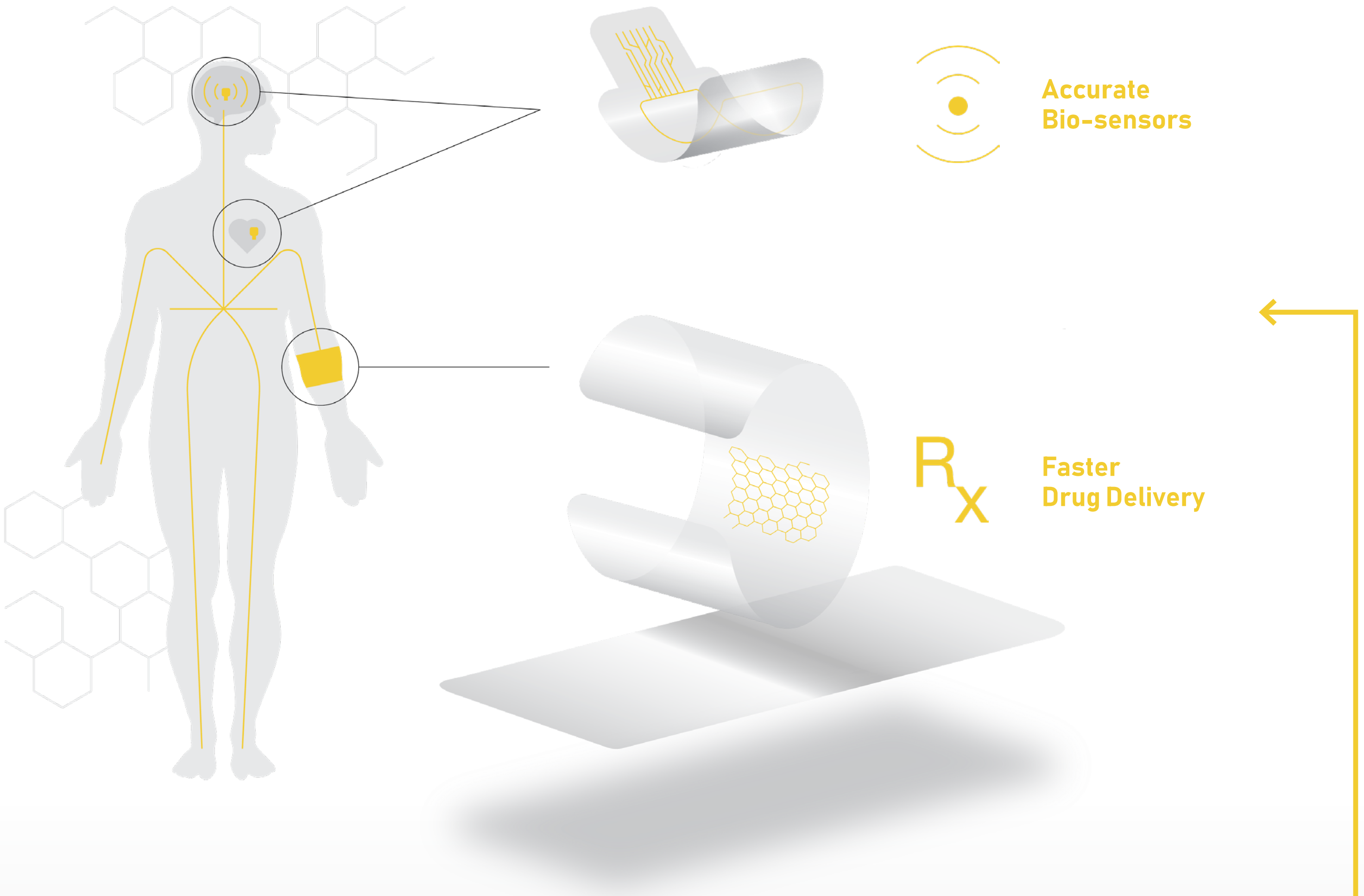
Multiple Discoveries for Making Graphene from Coal



One of NETL's patent-pending graphene manufacturing processes uses a proprietary pyrolysis process that converts lignite, bituminous and anthracite ranks of coal directly into a graphene-like material that is ideal as an additive for large scale fabrication of construction materials, polymer composites, and battery materials.

NETL's manufacturing method addresses cost challenges by using inexpensive domestic coal feedstocks, along with simple processing methods that help bring down production costs.

A second manufacturing process developed at NETL utilizes coal in a vapor-phase growth method to make incredibly high quality and low defect films of graphene that are only about three atomic layers thick.

This exceptionally high quality graphene has incredibly unique electrical conductivity properties that can be leveraged for use in computer electronics and as a sensing material in medical devices that detect disease in humans. This manufacturing process also reduces the cost of producing graphene and brings new manufacturing processes and companies into the market place, which will help bring down prices.

"With one of our low-cost graphene materials, we've been able to produce large samples of graphene-enriched cement, which has an improved mechanical strength and performance. These enhancements are imparted to the cement at a far lower cost than using conventional additives such as silica fume or carbon fiber. Construction materials may be just one of many application areas where our coal-based graphene proves to be a game changer," said NETL's Christopher Matranga, Ph.D.

"In addition to cement, we are using coal-based graphene to enable a new form of computer memory devices, called memristors. Our team is currently collaborating with researchers at the University of Illinois Urbana-Champaign on this topic and have figured out how to manufacture a coal-based graphene that helps improve the performance, energy efficiency, durability, and costs of memristors." said Matranga. "Imagine having computer systems that enable the use of artificial intelligence, machine learning, and edge computing all because of a graphene material that is made from domestic coal. It is a complete rethinking of how to use coal."

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Recognizing the Potential

Industry leaders and other scientists have already seen the promises NETL's innovations, such as coal-based graphene, hold for becoming mainstream and address pressing economic and societal challenges.

As the only operating entity in the coal industry solely dedicated to emerging coal technology and developing new markets for coal, Wyoming-based Ramaco Carbon LLC recognized the benefits of working with NETL. That's why the two entities launched a cooperative research and development agreement to develop and commercialize technologies that manufacture high-value products from coal. For example, NETL and Ramaco are evaluating coal-based graphene as a biosensing material for detecting disease in humans.

"The ability to repurpose coal for manufacturing advanced carbon products and materials has tremendous implications for not only the economy in Wyoming where Ramaco Carbon is located, but for our nation and indeed around the world," said Randall W. Atkins, chairman and chief executive of Ramaco Carbon. "Affordable, high-quality graphene developed by NETL could bring many new high value products to market while creating a new higher-tech and environmentally friendly repurposing of the coal industry."

This partnership enhanced NETL's materials engineering and manufacturing capabilities by allowing Lab researchers access to coal-based manufacturing and 3D-printing facilities developed by Ramaco Carbon. NETL's coal-based graphene process is one example of an old resource used in a creative manner to address emerging real-world problems.

Other NETL partnerships include working with the University of Illinois Urbana-Champaign to develop graphene materials for computer memory devices and microelectronics. The Lab is also working with the Massachusetts Institute of Technology to evaluate graphene and related carbon materials for fabricating water filtration membranes.

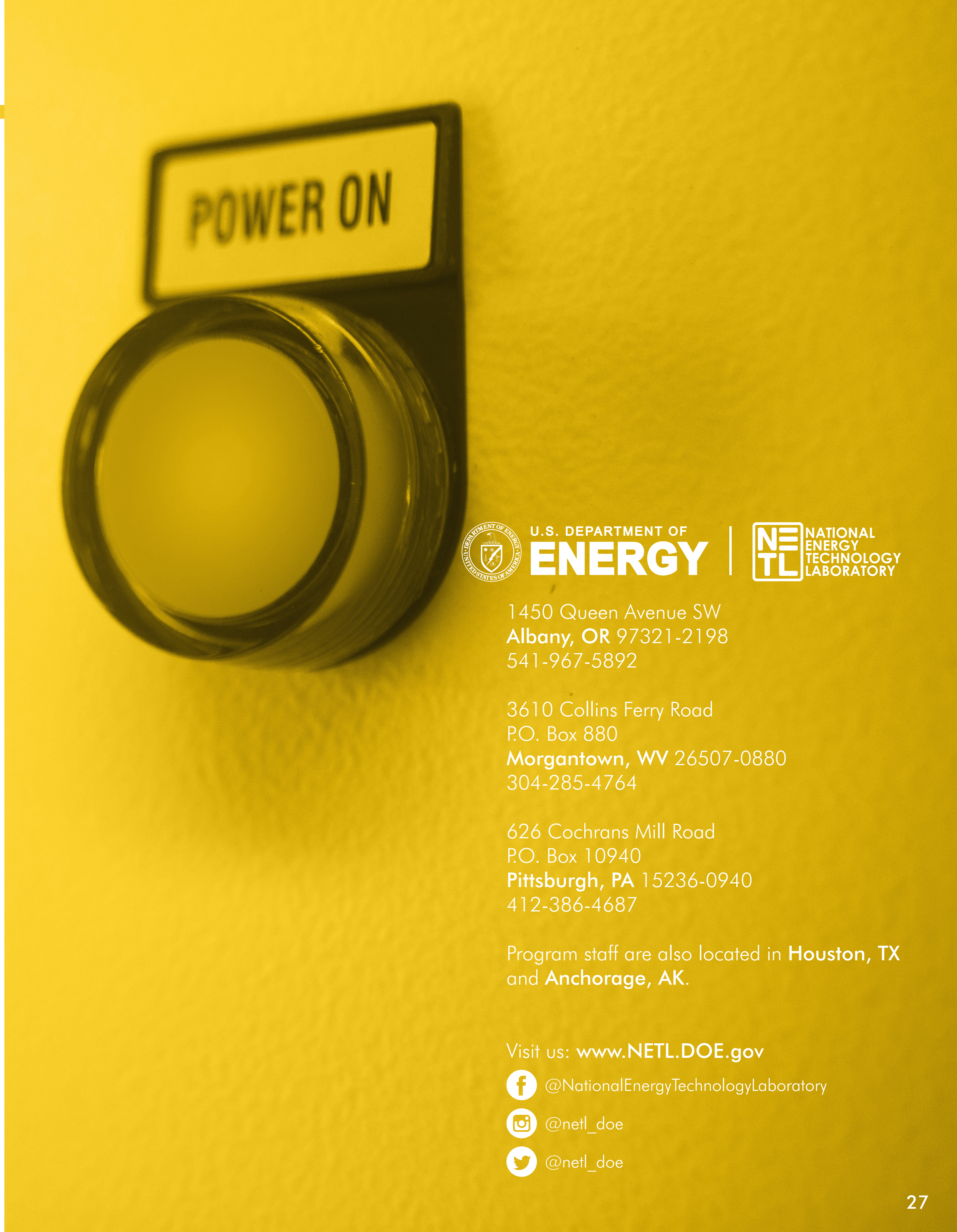
As a testament to its potential, Edgar Lara-Curzio, Ph.D., the co-director of Oak Ridge National Laboratory's Fossil Energy Program, gave words to the potential of NETL's coal-based graphene manufacturing process.

"The approach brings the total manufacturing costs in line with other specialty materials, such as carbon fiber, making the use of graphene in consumer products commercially viable," he said. "Low-cost coal-to-graphene is poised to bring a wave of improved consumer products to the market, and I have no doubt that NETL's breakthrough invention will have a transformational impact on industry and society."

With the world population growing and industrializing on a scale never seen before, the demand for durable building materials isn't slowing down any time soon. NETL's work to source graphene from coal can help meet this demand while making a positive impact in other areas.

For example, an affordable supply of graphene can enable its adoption on a larger scale, which will inspire exploration of new uses, which can spur even more demand. While its prohibitively high costs have slowed graphene's adoption, NETL's contribution not only navigates around this challenge but can potentially revitalize America's coal country through renewed demand for one of the nation's most abundant and reliable resources.

Small mining towns throughout the country, from Wyoming to Appalachia, provided the coal that powered and built our homes, cities, and communities. Research at NETL shows how coal can once again be part of a technological renaissance made possible by advanced materials, such as graphene. While many challenges still remain, NETL has shown that the solutions are perhaps closer to home and closer to realization than previously thought. ☰



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