Vol. 04/Issue 02
2023

NETL EDGE

A Publication of the U.S. Department of Energy's National Energy Technology Laboratory

FUTURE FUEL

Accelerating Hydrogen Technology for a Clean Energy Economy

NATIONAL ENERGY TECHNOLOGY LABORATORY

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Vol. 04/ Issue 02

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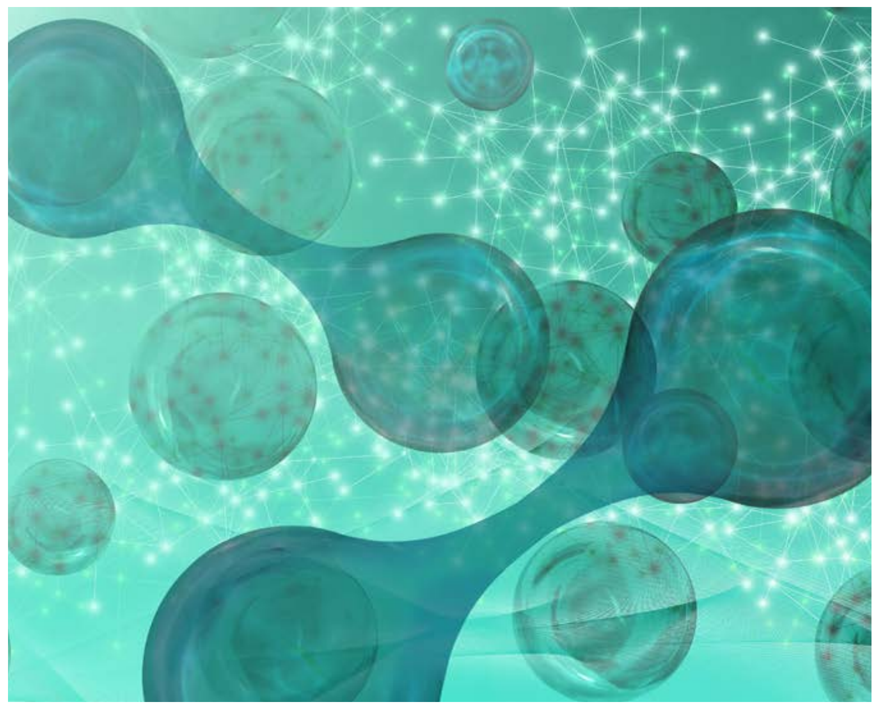
ON THE COVER



An alternative fuel that has very high energy content by weight, hydrogen consists of only one proton and one electron, and it is an energy carrier, not an energy source. Hydrogen can store and deliver usable energy. NETL's hydrogen research covers a range of topics associated with the drive to put hydrogen to work to meet the nation's energy needs and decarbonization goals.

DIRECTOR'S MESSAGE

America is on the threshold of a massive energy change that will have an equally massive effect on the planet's health and prosperity. NETL's work on hydrogen's role in that energy evolution is at the forefront of that shift. In this edition of NETL Edge, we are highlighting the work underway at NETL to develop and deploy safe, effective, wide-spread hydrogen-related technologies.

With a cadre of expert researchers and a growing collection of state-of-the-art research facilities, NETL is uniquely positioned to contribute key knowledge in the nation's hydrogen energy pursuit. The timing is right to expand and use that body of work. The Bipartisan Infrastructure Law and the Inflation Reduction Act, both signed into law by the president, provided research dollars, policies and incentives for hydrogen development.

This fall, I represented NETL at the Clean Energy Ministerial and Global Clean Energy Action Forum in Pittsburgh where more than 4,000 people from 35 countries gathered to take stock of clean energy efforts aimed at decarbonizing the planet. As Energy Secretary Jennifer Granholm told the attendees, "We're not just here to talk but to take concrete steps in our march toward a clean energy future."

One of those concrete steps was action by DOE to open applications for $7 billion in funding to establish up to 10 regional hydrogen hubs, a key step in DOE's "1 1 1" goal of reducing the cost of clean hydrogen by 80% to $1 per one kilogram in one decade.

John Kerry, special presidential envoy for climate, said in Pittsburgh that, "It's doable — for years, we just haven't been paying attention to it. I think that's why this room is full; people understand this is a new era."

Indeed, people are paying attention to the possibilities. At NETL, we look forward to being a key player in the hydrogen shift and the effort to establish hydrogen hubs to make that shift possible in locations throughout the country.

This edition of NETL Edge opens with a general explanation of our Laboratory's hydrogen production, transportation, and storage research portfolio and the critical role we play in supporting DOE's efforts to put hydrogen on the front lines of the attaining net-zero carbon emission goals by 2035.

Our magazine then explores NETL research on the co-gasification of waste plastics, biomass and coal for hydrogen production; explains how hydrogen can efficiently operate rotating detonation engines; and reviews our expanding role in a new national laboratory consortium that is finding ways to use electrolyzers to reduce the cost of hydrogen production from electricity. Finally, we will take a glimpse into the research life of NETL's Don Ferguson, whose leadership and service inspires a new generation of energy researchers.

We hope our readers will find these stories helpful primers on the potential of hydrogen to revolutionize and decarbonize the world and the important role NETL has assumed in making significant progress in that arena.

Thank you for your interest in NETL.

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

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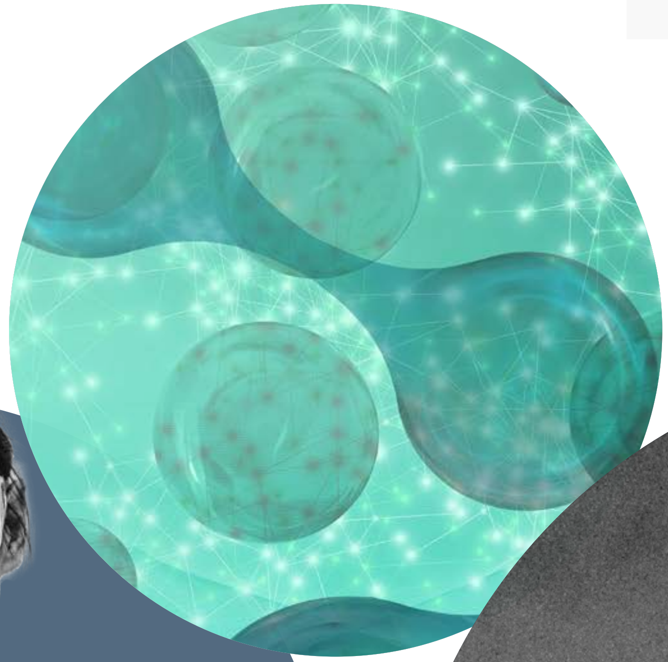


NETL Positioned as a Key Research Partner for Advancing a Hydrogen Energy Economy

By Gerrill Griffith

The production and application of hydrogen will develop just as rapidly in the next decade as was the case with wind and solar energy in the nineties.

- Prof. Stefan Reichelstein, senior fellow at Stanford Institute for Economic Policy Research and director of the Institute for Sustainable Energy, University of Mannheim,

Whether it's testing new concepts in its own laboratories, teaming with colleagues at sister national laboratories, collaborating with researchers in academia, sharing ideas with private sector companies or participating in global confabs to exchange breakthrough data, NETL is working to accelerate the rapid production and application of hydrogen technologies to build a new decarbonized energy economy.

NETL maintains a hydrogen production, transportation and storage research portfolio that makes it a key player in DOE initiatives to put hydrogen on the front lines of the effort to attain net-zero carbon emission goals in the power sector by 2035 and the broader economy by 2050, while meeting DOE's Hydrogen Shot goal of $1 per 1 kilogram in one decade.

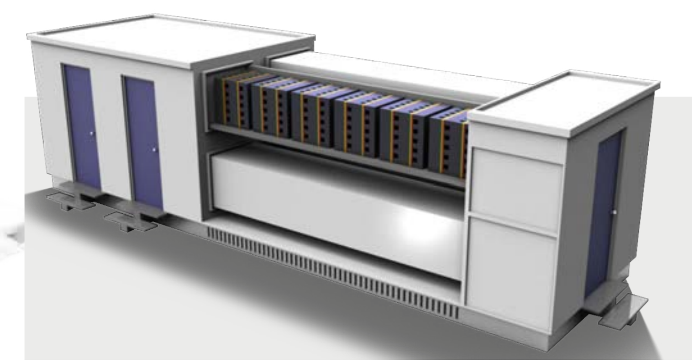
Currently, hydrogen from renewable energy costs about $5 per kilogram. Achieving the Hydrogen Shot's 80% cost reduction goal can unlock new markets for hydrogen in areas like steel manufacturing, clean ammonia production, energy storage, and heavy-duty trucks while creating more clean energy jobs, reducing greenhouse gas emissions, and positioning America to compete in the clean energy market on a global scale. DOE's Hydrogen Shot establishes a framework and foundation for clean hydrogen deployment.

According to DOE, if the Hydrogen Shot goals are achieved, scenarios show the opportunity for at least a fivefold increase in clean hydrogen use. A U.S. industry estimate shows the potential for 16% carbon dioxide (CO_2) emission reduction by 2050, $140 billion in revenues and 700,000 jobs by 2030.

Hydrogen is an alternative fuel that has very high energy content by weight. Hydrogen consists of only one proton and one electron, and it is an energy carrier, not an energy source. Hydrogen can store and deliver usable energy. NETL's hydrogen research covers a range of topics associated with the drive to put hydrogen to work to meet the nation's energy needs.

When used in fuel cells, for example, hydrogen can be used to power buildings, cars, trucks, portable electronic devices and backup power systems. Compared to conventional gasoline vehicles, fuel cell vehicles can reduce CO_2 by up to half, if the hydrogen is produced using natural gas, and by more than 90%, if the hydrogen is produced using renewable energy resources.

There are also no pollutants emitted from vehicle tailpipes — just water. In addition, because fuel cells can be grid independent, they are attractive for critical load functions like data centers, telecommunications towers, hospitals, emergency response systems and even military applications for national defense.



Fuel cell and electricity generation applications for hydrogen research are just part of NETL's overall hydrogen effort. NETL Director Brian Anderson, Ph.D., said a hydrogen future is about more than energy alone because it can help clean up sectors of the economy that are difficult to decarbonize.

At a presentation at the Massachusetts Institute of Technology, Anderson said, "When paired with carbon capture projects, hydrogen power — sourced from our country's vast fuel resources — presents exciting opportunities to decarbonize power plants and industrial facilities that produce cement, steel and other industrial products."

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Hydrogen Hubs

DOE announced in late September that it will be accepting applications to establish up to 10 regional hydrogen hubs, part of a broader road map to lower emissions in industrial sectors such as energy, transportation, steel and cement. DOE plans to select six to 10 hubs for a combined total of up to $7 billion in federal funding.

The plan was unveiled during the Global Clean Energy Action Forum (GCEAF) meeting in September 2022 in Pittsburgh that was attended by energy leaders from more than 35 nations.

Geographic diversity that includes broad groups of hydrogen stakeholders: companies, government agencies, producers and consumers, pipelines and transportation companies are expected to be reflected in the hub applications.

The hubs will demonstrate low-carbon intensity and economically viable hydrogen-based energy ecosystems that can replace existing carbon-intensive processes, attract greater investments from the private sector and promote substantial U.S. manufacturing of numerous hydrogen related technologies.

Each hub will include multiple partners that will bring together diverse hydrogen technologies to produce and utilize large amounts of hydrogen in different ways. These clean hydrogen demonstrations will balance hydrogen supply and demand, provide connective infrastructure, and offer a plan for long-term financial viability. The hubs will also include substantial engagement of local and regional stakeholders, as well as tribes, to ensure that they generate local, regional and national benefits.

To support the goals of building a clean and equitable energy economy, hub projects are to include a community benefits plan to support meaningful community and labor engagement; invest in America's workforce; advance diversity, equity, inclusion and accessibility; and contribute to the goal of making sure that 40% of the overall benefits of certain federal investments flow to disadvantaged communities.

NETL is well positioned to assist in bringing hydrogen production and storage technologies to bear by building upon a broad range of existing activity.

NETL Hydrogen Production Research

Hydrogen doesn't typically exist by itself in nature and must be produced from compounds that contain it. It is locked up in enormous quantities in water, hydrocarbons and other organic matter.

According to DOE's Alternative Fuels Data Center, hydrogen can be produced from domestic resources like fossil fuels and biomass, as well as from water electrolysis. The environmental impact and energy efficiency of hydrogen depends on how it is produced and where it comes from.

The production of hydrogen currently relies on steam methane reforming, which is energy intensive and releases CO_2. NETL is supporting research to explore alternative pathways of hydrogen production, including via methane pyrolysis, which directly converts methane into solid carbon and hydrogen gas.

The Laboratory has conducted an independent assessment of the cost and performance of select hydrogen production plants using fossil fuel resources as the primary feedstocks. The work also noted potential pathways for performance improvements and cost reductions, which NETL is assessing in a follow-up study to be published soon.

Anderson said funding for hydrogen economy research is growing with $9.5 billion included in the Bipartisan Infrastructure Law, with $8 billion of that dedicated for hydrogen hubs.

"This support demonstrates the success of other projects that have been ongoing for years," Anderson said. "An example can be seen in one of NETL's major carbon capture and sequestration projects in Port Arthur, Texas. It is successfully combining carbon capture with steam methane reforming to produce hydrogen. For a single production stream, the project can capture over 90% of the carbon for production of clean hydrogen. The project has captured over 7 million tons of CO_2 since 2013. This is but a sample of what can happen when we all work toward a common goal."

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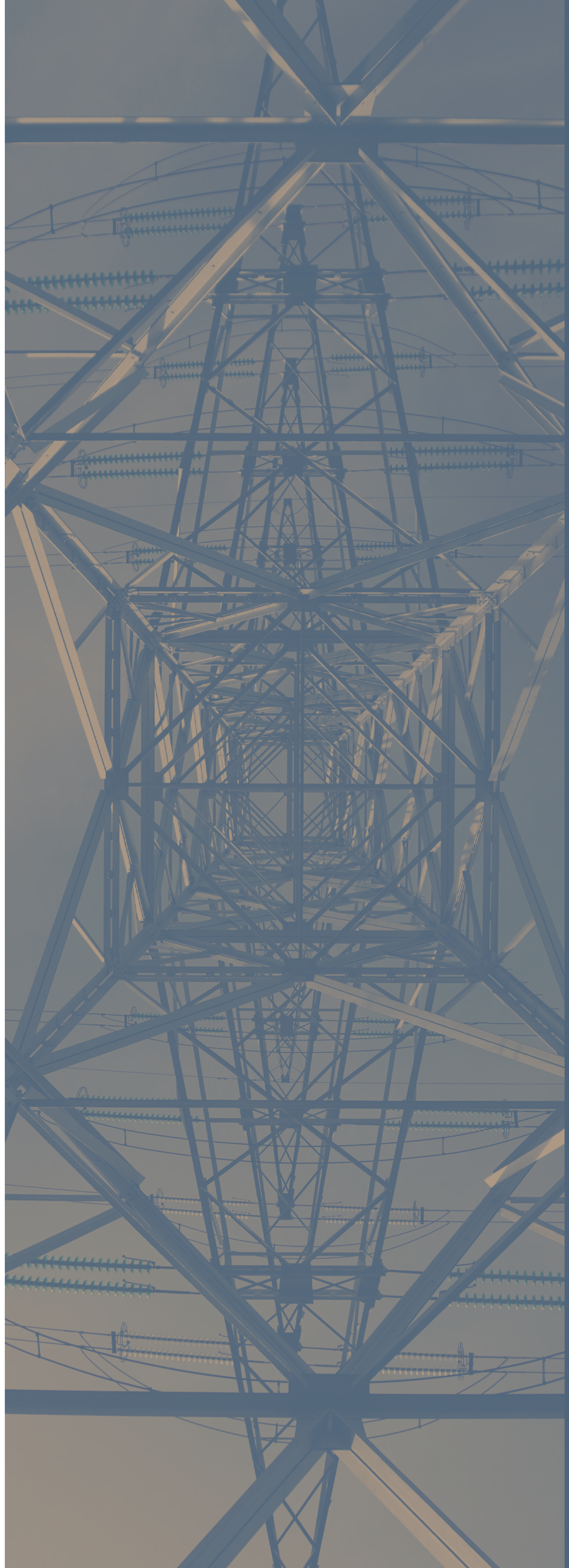
NETL Research Partnerships for Generating Electricity with Hydrogen

One major way NETL pursues research to make hydrogen a more available and effective fuel for electricity generation is through support of private sector research on advanced technology solutions. For example, NETL is working with:

- **8 Rivers Capital LLC (Durham, North Carolina)** to complete an engineering design study for a new hydrogen production plant that produces 99.97%-pure hydrogen and captures 90–99% of CO_2 emissions.
- **Gas Technology Institute (Des Plaines, Illinois)** to study the use of ammonia-hydrogen fuel mixtures in gas turbines to potentially strengthen the use of ammonia as a clean low-carbon fuel for electricity generation.
- **General Electric Company (Greenville, South Carolina)** to develop and test gas turbine components with natural gas-hydrogen fuel mixtures up to 100% hydrogen, to study and address combustion challenges associated with burning highly reactive hydrogen fuels.
- **General Electric, GE Research (Niskayuna, New York)** to study the operation of hydrogen-fueled turbine components, which could substantially improve gas turbine efficiency for both simple- and combined-cycle power generation applications.
- **Raytheon Technologies Research Center (East Hartford, Connecticut)** to develop and test the effectiveness of natural gas turbine engine components in high-temperature rigs using natural gas-hydrogen fuel mixtures with increasing hydrogen content.
- **Raytheon Technologies Research Center (East Hartford, Connecticut)** to study, develop and test an ammonia-fired gas turbine combustor that generates low nitrous oxide emissions, with robust operability and stability for greater than 99.99% efficiency.



Hydrogen Storage Research — NETL and DOE's SHASTA

One of the most significant obstacles to implementing the transition to hydrogen energy use is the need for energy storage to compensate for varying, and sometimes intermittent, production rates and ever-increasing demand. An attractive solution is to use surplus renewable energy and water to produce hydrogen via electrolysis, which can then be used to produce electricity on demand without emitting CO_2. NETL researchers are engaged in discovering the feasibility and challenges of underground geologic storage of hydrogen to meet future energy needs.

Renewable energy sources such as wind, hydroelectric, solar, biomass and geothermal are an increasing portion of the total energy supply mix helping to reduce CO_2 in the atmosphere. However, dealing with the intermittent supply associated with those energy sources and varying demand for energy is a key challenge.

Energy experts see an answer to the challenge in converting energy produced by renewable sources into hydrogen and then storing it for future demand. NETL researchers are at work independently and as members of a unique multi-national laboratory team to make that approach feasible.

Natural gas has been stored in depleted oil and gas fields, saline aquifers and salt caverns for decades. However, the impacts of underground hydrogen storage on reservoirs, hydrogen leakage risks, and flow behavior of hydrogen and blended mixtures are not well understood. The new demand for widely available hydrogen sources and opportunities to use hydrogen blended with natural gas will require storage reservoirs at locations across the United States.

"Underground storage of hydrogen is less costly than storage in above-ground vessels," Angela Goodman of NETL's Biogeochemistry and Water Team explained. "But the technical challenges must be addressed. We are teaming with other national laboratories to focus on quantifying materials compatibility and investigating potential microbial interactions."

She said NETL researchers are working with colleagues at the Pacific Northwest National Laboratory, the Lawrence Livermore National Laboratory and Sandia National Laboratories under a research umbrella known as SHASTA — Subsurface Hydrogen Assessment, Storage, and Technology Acceleration — to generate knowledge leading to effective widespread use of underground storage for the nation's hydrogen and the energy it can bring to bear on decarbonization efforts.

DOE's Office of Fossil Energy and Carbon Management organized SHASTA. Researchers within SHASTA are determining the viability, safety and reliability of storing pure hydrogen or hydrogen-natural gas blends in subsurface environments.

Goodman said NETL experts are supporting the SHASTA initiative by addressing a range of challenges including:

- Hydrogen storage feasibility in a variety of underground systems.
- Hydrogen gas behavior during storage.
- Hydrogen loss through biogeochemical reactions.
- Risks of loss of containment from storage reservoirs, through caprock, faults, fractures or leaky wells.
- Development of real-time monitoring technologies to assure storage integrity and safety.
- Levels of support from key stakeholders and the public.
- Expected regulatory environment.

"Our work builds on existing subsurface capabilities that were designed to study wellbore and subsurface reactions," Goodman said. "The Lab's capabilities will also be used to assess the geochemistry and microbiology of reservoir types targeted for storage and to develop optic fiber sensors needed to monitor underground storage."

H2NEW INITIATIVE

NETL Modeling Work to Bolster National Laboratory Collaboration Focused on Clean Hydrogen Production

By Joe Golden

With increased funding and an expanded role in DOE's Hydrogen from Next-generation Electrolyzers of Water (H2NEW) initiative, NETL is ramping up work with other national laboratories to improve the cost-effectiveness of producing hydrogen through high-temperature electrolysis.

"There's more than one way to produce hydrogen, but electrolysis cells only require water and electricity, so they are cleaner than any other method," said NETL's Harry Abernathy, who leads the NETL team in the H2NEW initiative. "Unfortunately, electrolysis is also more expensive than methods such as steam methane reforming, making cost the most obvious barrier to overcome."

Specifically, Abernathy's team at NETL and the other national laboratory partners, which include the Pacific Northwest National Laboratory (PNNL), the National Renewable Energy Laboratory (NREL), Idaho National Laboratory (INL), Lawrence Livermore National Laboratory (LLNL) and Lawrence Berkley National Laboratory (LBNL), are trying to help realize DOE's goal of reducing hydrogen production costs to under $2 per kilogram by 2025 (and $1/kg by 2030 as part of the DOE's Hydrogen Shot), which would make electrolysis cost-competitive with fossil-derived hydrogen.

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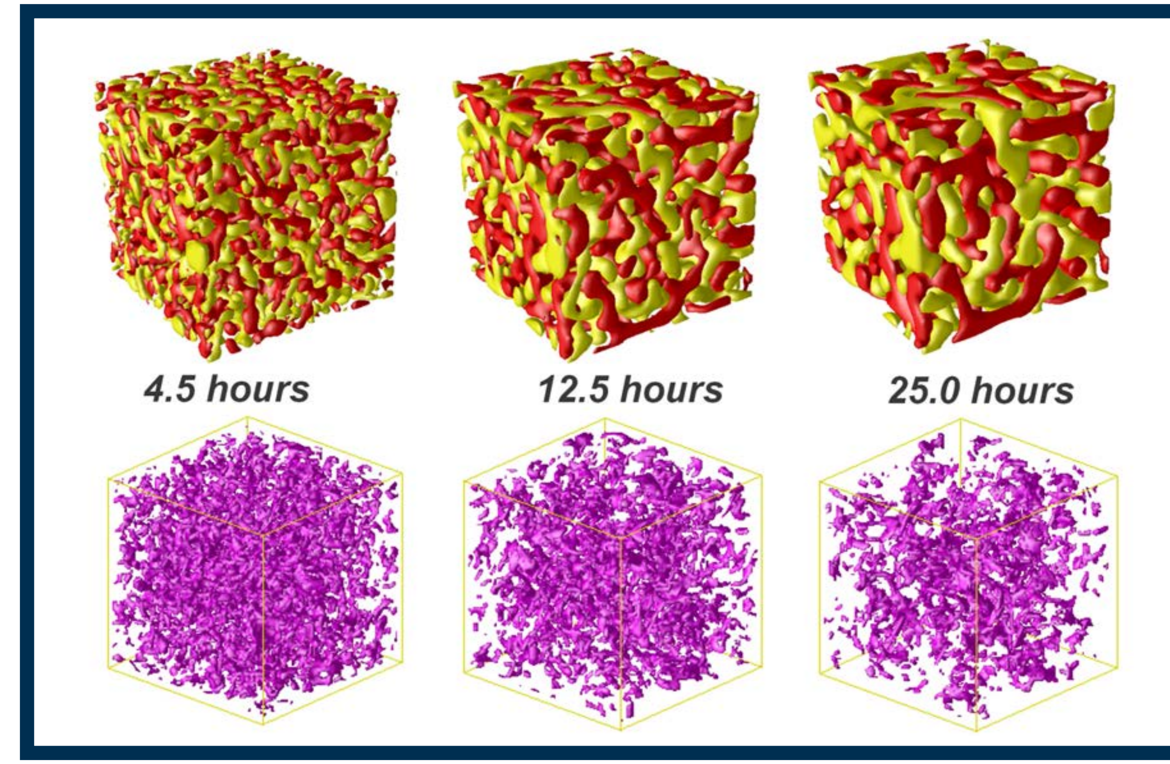
To overcome the cost barrier, high-temperature electrolyzers (HTEs) must be fabricated at scale, use low-cost electricity more efficiently, and demonstrate durability. Understanding what to adjust in an electrolysis cell to make it perform better and last longer is where NETL's expertise comes into play.

"NETL has extensive experience in the development and testing of solid oxide fuel cells (SOFCs), which are structurally and chemically the same as the HTEs we are investigating with the other national labs in this initiative," Abernathy said. "The only difference between the two is that for a SOFC you're turning fuel into electricity — like a battery — while for an HTE, you are pumping electricity into the device and generating fuel (in this case, hydrogen)."

One of the primary obstacles to widespread commercialization of SOFCs as well as HTEs is degradation, a gradual decline in performance that limits a cell's practical lifespan. Several suspected contributors to performance degradation are tied to the fuel cell's microstructural composition.

NETL researchers have been examining SOFCs with powerful microscopes and using advanced 3D imaging techniques to reveal their changing microstructures during operation. They then paired those observed changes with experimental performance data from cells to develop performance degradation models based on chemistry, physics and real data.

"We have used the Lab's cutting-edge computational tools to model thousands of simulated microstructures and developed an integrated modeling framework that aims to predict performance degradation for SOFC electrode microstructures," Abernathy said. "The information and tools are directly applicable to the HTEs in this investigation."



An NETL SOFC degradation model.

A researcher places SOFC button cells in NETL's multi-cell array testing platform for analysis.

The computational tools identify performance-relevant properties based on the cell's initial microstructure and incorporate a multiphysics model, which predicts cell performance based on its microstructure, and a coarsening model, which anticipates microstructural changes during operation.

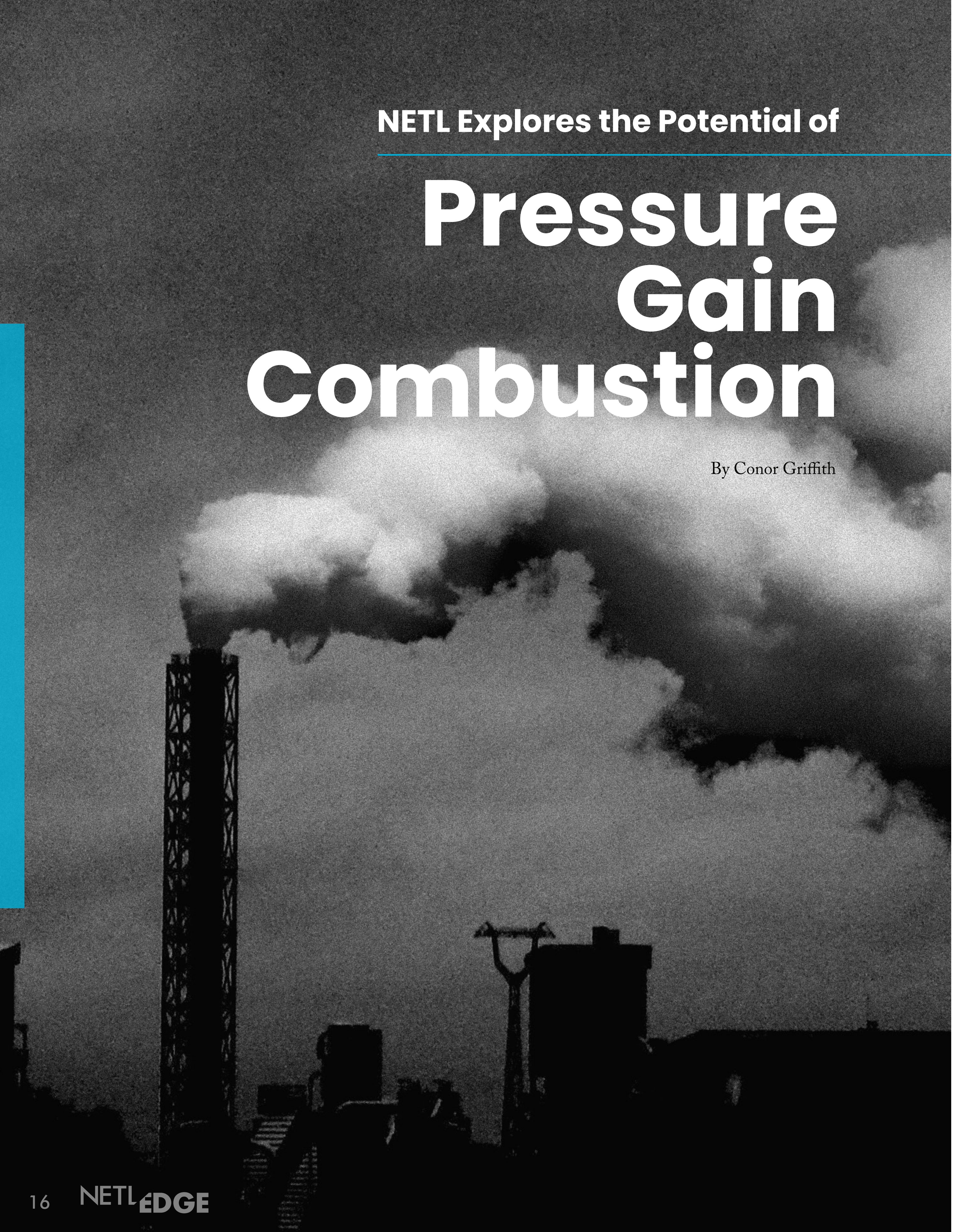
To date, NETL has examined a vast library of 45,000 synthetic microstructures using its supercomputer Joule 2.0, representing the largest variety of microstructural possibilities known within the fuel cell world.

As part of the new initiative work, the Lab will use the analytical software tools developed in-house to help analyze HTE microstructural characterization data being collected by NREL and PNNL.

The team will also combine its degradation models with those developed by LLNL to simulate the degradation of HTEs based on the baseline samples being run by partner labs doing the experimental work — PNNL, INL and LBNL.

The NETL team will finally use machine learning capabilities to analyze the degradation simulation data to determine which features of the HTE electrodes must be targeted to make a longer-lasting, higher-performing device.

"These highly efficient, ultralow-emission HTE technologies are uniquely suited to address environmental concerns associated with hydrogen production," Abernathy said. "This initiative (H2NEW) is helping to meet clean energy goals that call for a net-zero carbon emission electricity sector by 2035 and economy-wide net-zero emissions by 2050."



NETL Explores the Potential of

Pressure Gain Combustion

By Conor Griffith

A recently commissioned rotating detonation engine (RDE) test rig at the Lab's campus in Morgantown, West Virginia, is creating opportunities for hydrogen combustion that will help to decarbonize the U.S. economy.

By mass, hydrogen has more stored energy than conventional fuels. But burning hydrogen as a fuel can be difficult in devices like gas turbine engines for power generation, as fast flame speeds and high flame temperatures create challenges such as unstable combustion and high oxides of nitrogen (NOx) emissions. Detonation combustion may offer the possibility of using hydrogen free of these challenges and also improve process efficiencies, leading to lower costs and the ability to burn less fuel. This directly supports the objectives of the Office of Fossil Energy and Carbon Management (FECM) to advance utility-scale technologies that operate on 100% hydrogen.

Utilizing detonation, RDEs perform a process known as pressure gain combustion (PGC) in which greater energy can be extracted from the fuel compared to the more common form of combustion known as deflagration. This additional energy can be converted to useful work making the detonation process more fuel efficient. This is an advantage not only for land-based power generation, but for aerospace applications that are also aggressively pursuing RDE technologies for rockets.

NETL was one of the first laboratories in the nation to study PGC using a water-cooled RDE. While most research facilities studying this phenomenon were limited to test times of one to two seconds, NETL has been able to run for extended periods of time, only limited by fuel supply. This has allowed NETL to explore aspects of RDE operation such as transient and thermally stable conditions, which will be critical for power generation requiring load following and base load.

The new RDE test rig, located alongside the water-cooled RDE in the Lab's Thermal Sciences Research facility, has several unique capabilities that will help advance the technology to market. First, the new experiment provides optical access to the fuel and air injectors, combustion chamber and exhaust, which will allow researchers to better understand the strong coupling that exists between these components by using advanced laser and optical diagnostics. These methods will help characterize the formation pathways for NOx emissions and loss mechanisms that may hamper adoption into technologies such as gas turbine engines.

"NOx are regulated emissions from power plants as well as other technologies such as automotive and aircraft engines," said Don Ferguson, NETL research mechanical engineer and principal investigator for the PGC project. "It is important, when developing a new combustion technology, to understand how the new process could impact NOx emissions. Research thus far has shown NOx emissions from the RDE to be on par with today's state-of-the-art low NOx gas turbine engines."

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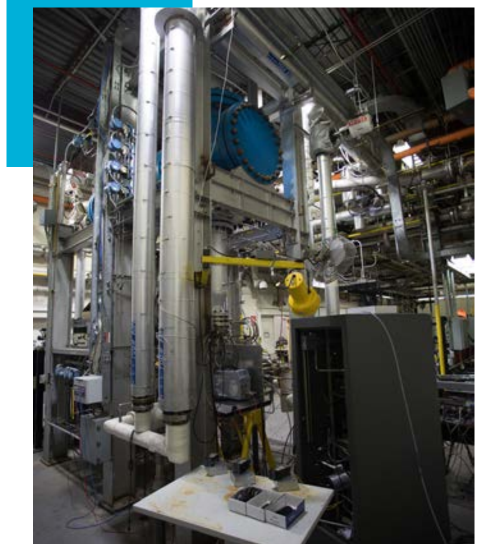
Fostering U.S. Decarbonization

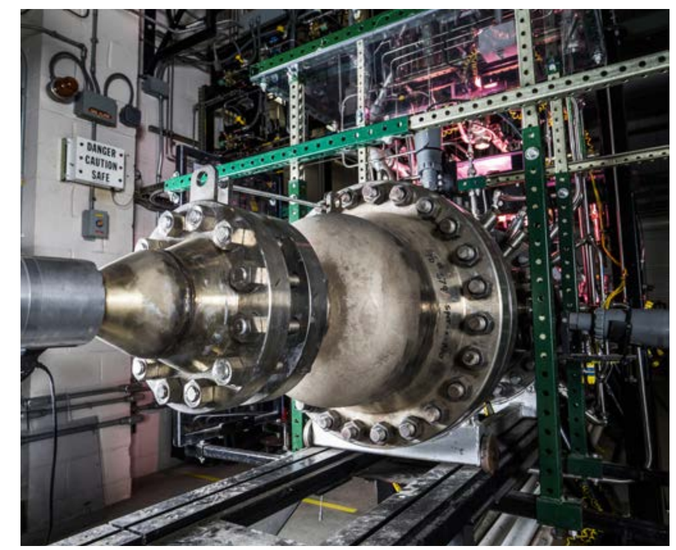
Using RDEs enables two basic, but related, approaches for decarbonization.

The first approach is rooted in the fact that detonation has an inherent efficiency advantage compared to deflagration combustion. This means a process using RDEs could produce more work for the same amount of fuel compared to conventional engine designs. For carbon-containing fuels, such as natural gas, this would emit fewer carbon emissions per kilowatt resulting in an immediate reduction in carbon dioxide emissions from power plants using RDEs.

The second approach focuses on carbon-free fuels such as hydrogen. As previously noted, hydrogen is challenging to use as a fuel due to its very fast flame speeds often resulting in various forms of combustion instabilities. Because RDEs utilize detonation that is designed to occur at supersonic speeds, problems like flashback, where the flame moves upstream into the injector potentially resulting in catastrophic failure, can be avoided. NETL conducted an extensive study on flashback in hydrogen flames in the early 2000s, and lessons learned from those studies are being applied to RDEs as well as more conventional combustion applications for gas turbines and other processes.

NETL, through its research on hydrogen production, transportation, storage and use, is playing a critical role in DOE's efforts to put hydrogen on the front lines of efforts to attain net-zero carbon emission goals in the power sector by 2035 and the broader economy by 2050.





Other Practical Applications for Rotating Detonation Engines

As a means of stable combustion for carbon-free fuels like hydrogen and possessing the ability to increase the combustion pressure through the detonation wave, RDEs are being considered in numerous applications.

"Two general industries that are actively pursuing RDE technology include energy and aerospace," Ferguson said. "DOE is exploring the integration of an RDE into a gas turbine engine as a means of increasing the overall cycle efficiency, thus producing fewer carbon emissions for carbon-containing fuels and as a means of stable hydrogen combustion."

Ferguson continued, "RDEs offer a unique capability to develop an entirely new power cycle that produces electricity with no moving parts. This could potentially result in a considerable saving associated with maintenance costs at power plants. The aerospace industry is also spending millions of dollars to design rockets and aircraft that can use RDEs for direct impulse power. One of the primary advantages of RDEs is that they can be made much smaller than conventional combustion systems while still producing an equivalent amount of thrust. This results in a significant weight and volume savings that can increase the distance traveled or payload."

MAXIMIZING THE HARVEST TO PRODUCE CLEANER ENERGY

By Martin Kinnunen

NETL Feedstocks for Hydrogen Production Will Range from Agricultural Biomass to the Plastic Bags Used to Carry Food Home

On a sunny autumn morning perfect for the fall harvest, NETL researcher Pranjali Muley reached into a jar and pulled out a handful of corn stover — a coarse mixture of stalks, leaves, husks and tassels gleaned from a farmer's field.

"This is one of the feeds used in cogasification, a process that can blend biomass, waste plastic and coal feedstocks under high pressure and temperature to produce synthesis gas, or syngas, a commodity from which we can obtain hydrogen, a clean fuel to mitigate the impact of climate change," Muley said.

The planet-friendly benefits of cogasification don't end there.

The U.S. Environmental Protection Agency estimates that less than 9% of plastic material generated in the U.S. municipal solid waste stream is recycled. The remainder and, for that matter, much of the world's plastic is landfilled or simply dumped. As a result, millions of tons of plastics end up in rivers, lakes and oceans, destroying marine life and damaging ecosystems.

Plastic generally takes tens to hundreds of years to degrade. Even then, it becomes microplastics, without fully decomposing. According to the Intergovernmental Oceanographic Commission of the United Nations Education, Scientific and Cultural Organization, 50-75 trillion pieces of plastic and microplastics are in the oceans.

"We can reduce the flow of plastics into the world's oceans and landfills by using it as a feedstock for clean energy," said Mark Smith, Muley's colleague on the NETL Reaction Engineering Team. "For me, that's the holy grail right there."

To fulfill that vision, NETL, a world leader in gasification technology, is conducting significant research to advance its expertise in the field.

Gasification is a process that converts carbonaceous (carbon-based) raw materials into syngas. Gasification occurs in a gasifier, generally a high-temperature, high-pressure vessel where controlled amounts of oxygen (or air) and/or steam are directly contacted with the feedstock material causing a series of chemical reactions.

It sounds like combustion, but it's not. Combustion uses an abundance of oxygen to produce heat and light by burning. Gasification uses only a small amount of oxygen, which is combined with steam under intense pressure. This initiates a series of chemical reactions that produce a gaseous mixture composed primarily of carbon monoxide and hydrogen. The syngas can be burned directly or used as a starting point to manufacture pure hydrogen as well as fertilizers, liquid transportation fuels, other chemicals and value-added products.

Cogasification can involve the use of waste plastics (such as plastic water bottles and shopping bags, which are made from oil and natural gas and have a large carbon footprint) and diverse biomass feedstocks such as wood chips, sawdust or the corn stover in Muley's jar and breaks them down into the molecular building blocks for syngas.

NETL's advancements in the use of blended and variable feedstocks are intended to enable cogasification technology that will perform reliably and flexibly to produce hydrogen for a net-zero carbon emissions future. Currently, NETL researchers are exploring the topic from multiple angles.

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Microwaves for Cogasification

Hydrogen produces only heat and water when used as an energy source, which explains why affordable production of hydrogen for use in fuel cells to power vehicles or in turbines to generate electric power are priorities as NETL works to support the government's 2050 net-zero emissions goal.

Muley, Smith and their colleagues in the Lab's state-of-the-art Reaction Analysis and Chemical Transformation (ReACT) facility are using microwaves to generate hydrogen-rich syngas from biomass, waste plastics and coal.

Traditional heating of gasifiers to promote chemical reactions is both costly and energy intensive. Microwaves, on the other hand, can rapidly heat reactants to extremely high temperatures without heating the entire reactor volume. Furthermore, microwaves enable researchers to achieve desired temperatures quickly, which minimizes startup and shutdown times, saves additional energy and selectively targets the reacting materials. These unique properties of microwave heating allow gasification to occur at lower bulk temperatures and with shorter reaction times.

The Reaction Engineering Team has investigated reaction parameters such as plastic-biomass ratio, temperature, gasifying agent and heating techniques (microwaves versus conventional) to find the ideal conditions for plastic gasification with maximum hydrogen yield. Three different types of plastics, including polystyrene (Styrofoam), were processed into a powder and used in the study.

Their lab-scale studies found that a 1-to-1-to-1 ratio of plastic, biomass (corn stover) and silicon carbide was the optimal mixture to produce clean hydrogen. The volume of hydrogen produced at 700 degrees Celsius using microwave technology was substantially greater than the amount of hydrogen produced at 700 to 950 degrees Celsius using conventional heating.

The microwave process also produced lower amounts of carbon dioxide. Plastic and biomass have a synergistic effect during gasification, which results in high hydrogen production. Microwave heating enhances this synergy.

"Much of the carbon is trapped as char, a solid carbon byproduct, which means lower greenhouse gas emissions from waste plastic processing."

"Much of the carbon is trapped as char, a solid carbon byproduct, which means lower greenhouse gas emissions from waste plastic processing," Muley said.

The char can then be used as a soil conditioner to improve soil structure by increasing aeration, improving water-holding capacity and adding nutrients. "The char is also a great product for use as activated carbon for water purification or to develop other products, including carbon nanotubes for advanced electronics," Smith said.

He and Muley said their research represents an important step toward the commercialization of plastic gasification for clean hydrogen production.

"Microwave heating has gained interest across a spectrum of chemical reactions due to its unique advantages over conventional heating techniques. As microwaves interact directly with the material, heating is rapid and volumetric. Also, the microwave's selective heating feature can reduce the bulk temperatures required to trigger the gasification reaction, which increases the overall energy efficiency and reduces operational costs," Smith said.

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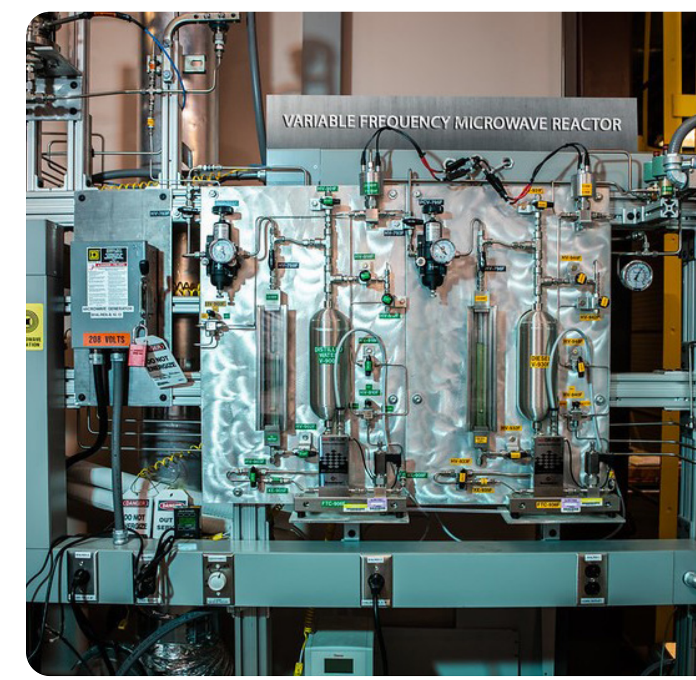

Finding *the* One-Step Process

The traditional commercial methods of forming hydrogen from methane, the primary component of natural gas, are based on steam methane reforming. This method requires that syngas first be created and the water-gas-shift reaction be used to convert syngas to hydrogen and carbon dioxide. From there, the hydrogen must be purified using pressure swing adsorption another separation process.

“Developing a method that avoids these intermediate steps reduces the cost of producing hydrogen,” said Ranjani Siriwardane, a research scientist at NETL for 34 years and one of the Lab’s most prolific researchers.

Siriwardane is the co-inventor of technology that relies on iron-based catalysts in a one-step process to produce hydrogen from methane using the thermal decomposition of methane (TDM) method. Elemental carbon consisting of nanotubes and nanofibers, which have immense value in industry, is also formed during the process.

Conventional TDM methods often employ environmentally hazardous catalysts such as nickel to activate the chemical reaction. Other catalysts containing supported iron and mixed metal oxides have been used. However, these catalysts failed to produce long-term stability and high conversions of methane to hydrogen.

NETL’s novel iron-based catalyst offers multiple advantages over conventional technologies to produce hydrogen.

“Our catalyst is environmentally safe and low-cost, and demonstrated continuous hydrogen production for 160 hours, with 80-90% methane-to-hydrogen conversion rates at 700 degrees Celsius during fluidized bed tests. The observed activity of NETL’s catalyst is unprecedented as there are no test results reported in the scientific literature showing similar activity for such a long duration,” Siriwardane said.

“Plus, the carbon formed was identified as a valuable material for the production of carbon nanofibers and nanotubes,” Siriwardane said.

A nanometer is one-billionth of a meter, or about 10,000 times smaller than a human hair. Carbon nanotubes are unique because the bonding between the atoms is very strong. Unlike carbon fiber, which is typically used as a structural component in everything from golf clubs to car bodies, carbon nanotubes operate both as structural components and as conductors.

Those qualities have resulted in the development of carbon nanomaterials to fabricate computer memory technology with improved energy consumption, processing speeds, durability and reduced manufacturing costs. “Carbon nanotube computer chips may ultimately give rise to a new generation of faster, more energy-efficient electronics,” Siriwardane said.

Siriwardane has also worked to develop a non-catalytic oxygen carrier process for pure hydrogen production from solid fuels such as plastics, municipal solid waste (MSW), biomass or coal.

Industrial-scale hydrogen production via solid fuel gasification has traditionally involved large amounts of oxygen, typically produced using a cryogenic air separation unit, a costly process in which air is separated into its component gases by distillation at low temperatures.

To address this issue, Siriwardane led the development of a non-catalytic process that uses a metal oxide-based oxygen carrier to oxidize solid fuels.

After reacting with the solid fuel in the reactor, the resulting reduced metal oxides are re-oxidized using steam to produce pure hydrogen and partially oxidized metal. Heat required for the process is generated using air oxidation. The process requires a minimal external heat source and produces pure hydrogen and carbon dioxide, which is a greenhouse gas that can be captured for safe and permanent sequestration in deep geologic formations.

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

This patent-pending hydrogen production process has been demonstrated in bench-scale tests at NETL with various solid fuels. “It is remarkable that even MSW and plastics were able to reduce the oxygen carriers, resulting in more than 80% conversion of steam to hydrogen and stable performance in multi-cycle tests,” Siriwardane said.

DOE’s Energy Earthshots Initiative is intended to accelerate breakthroughs of more abundant, affordable and reliable clean energy solutions within the decade. The first Energy Earth shot, launched June 7, 2021, Hydrogen Shot seeks to reduce the cost of clean hydrogen by 80% to $1 per 1 kilogram in 1 decade (“1 1 1”).

“The catalytic and non-catalytic processes advanced by NETL are critical parts of the overall strategy to achieve the goals of the Hydrogen Shot and accelerate breakthroughs of more abundant, affordable and reliable clean energy solutions,” Siriwardane said.

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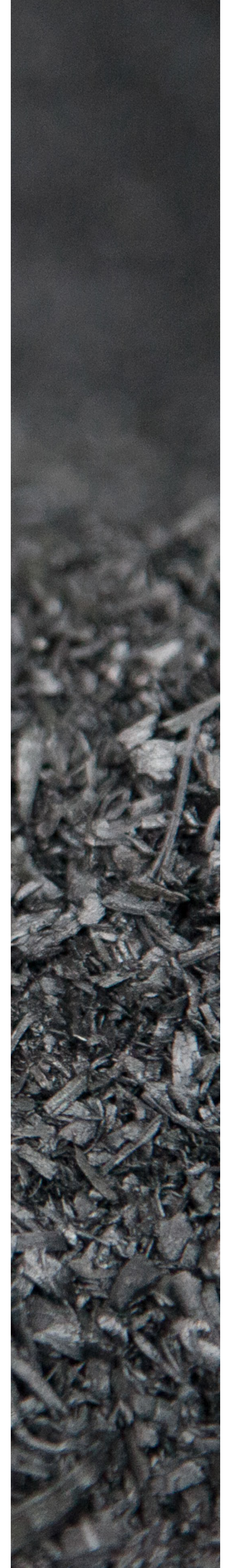


New Uses for Coal Wastes

Coal fines, also known as tailings, pose significant environmental risks. For example, run-off from slurry ponds or dumps containing the materials is often toxic because it contains harmful substances leached out of the coal, which then enter groundwater or pollute rivers and lakes.

However, in the hands of NETL researchers Fan Shi, Ping Wang, McMahan Gray, Jonathan Lekse and their colleagues, coal fines may no longer need to be stockpiled as a dangerous waste product. They can instead be combined with waste plastics in the gasification process to generate syngas from which hydrogen can be produced.

In bench-scale experiments, the researchers used a press to manufacture small pellets consisting of coal fines and pre-ground, low-density polyethylene, a plastic often used for the production of shopping bags, beverage jugs and other food packaging products. The pellets are then placed in a drop-tube gasification reactor to manufacture syngas.

"The gasification of plastics presents challenges. Due to the high volatile content of plastics, its gasification results in high tar formations," Wang said. "Tar is an undesirable byproduct because it can cause operational issues such as blockages and plugging within the gasification system, which can negatively impact gasification efficiency."

Cogasification of coal wastes and plastic resolves issues created by the stickiness of the plastic materials.

"The coal waste feedstock serves as a catalyst to convert the tar material to syngas. This opens new doors for hydrogen production while creating a viable use for millions of tons of unwanted plastics and coal fines. In addition to reducing the amount of plastic in the environment, the technology transforms a waste byproduct generated by mining into a resource that can bring good-paying, union jobs to U.S. communities tied to coal production," Shi said.

There are more than 20 distinct groups of plastics with hundreds of varieties. NETL's gasification development efforts provide sustainable solutions to chemically recycle a wider variety of plastics, including mixed, colored and multi-layer material plastic wastes.

"Cogasification of plastic with coal waste could catalytically enhance reforming reactions for hydrogen production, reduce the tar content of the gas phase product and resolve the feeding issue caused by the stickiness of the plastic," Wang said.

Wang, Shi and their colleagues are also using big data and tools such as machine learning to review the tremendous volume of technical research papers and reports devoted to waste plastic recycling/upcycling technologies. The work is focused on thousands of studies completed in the past 60 years and is designed to uncover hidden patterns, correlations and other insights for future studies.

Moving forward, Wang and Shi will lead research to optimize coal waste/plastic ratios for use as gasification feedstock. They also plan to study the use of biomass feedstocks such as sawdust and switchgrass in cogasification and investigate pretreatment steps to remove contaminants that can deteriorate sorbent materials that capture carbon dioxide emissions produced during gasification so they can be safely and permanently stored in geologic formations.

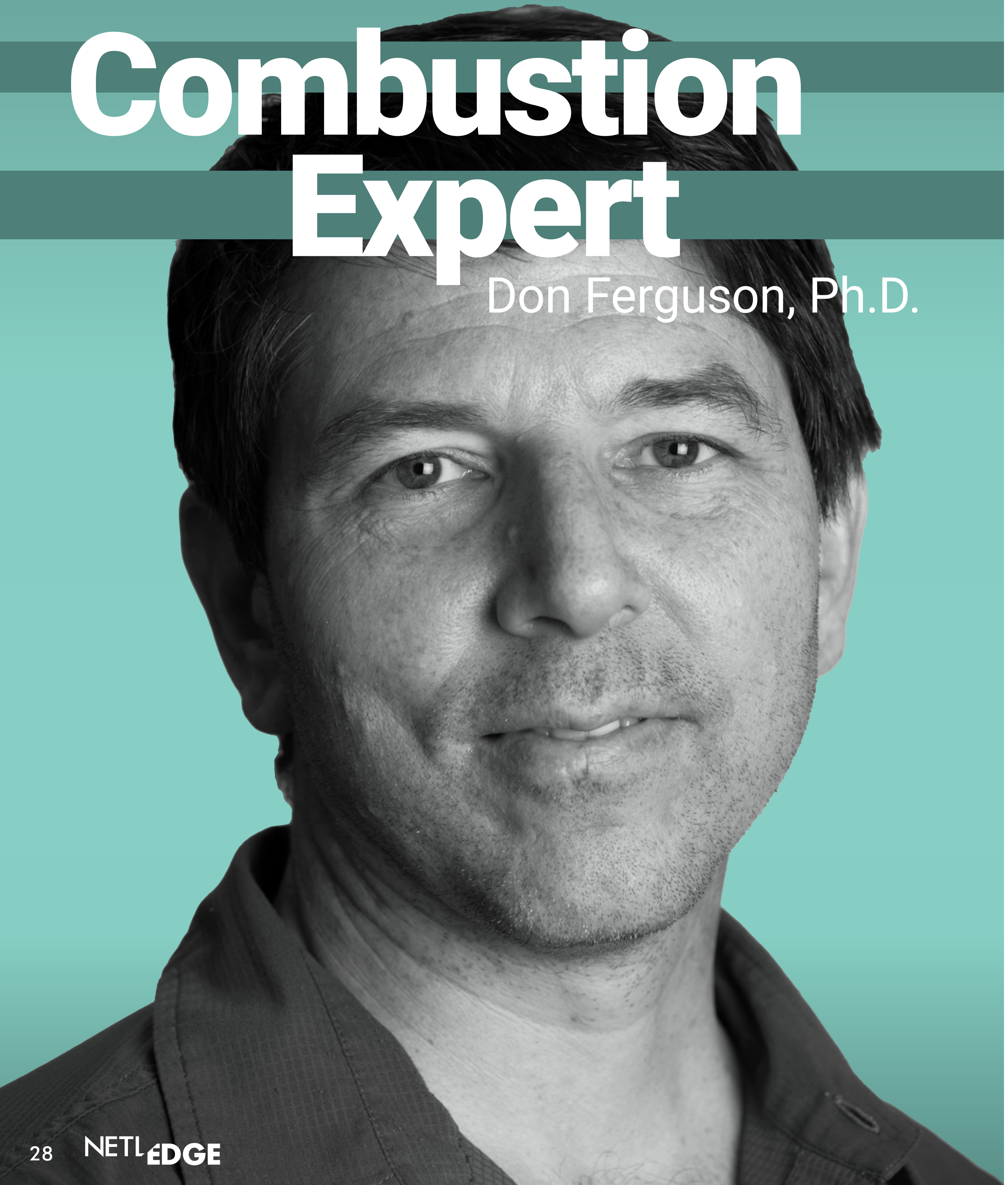
"Our ultimate goal is to produce hydrogen from waste plastics, biomass and coal waste with minimal carbon dioxide emissions. The use of these domestic resources to produce low-carbon-footprint hydrogen and chemicals can also help produce jobs through the creation of a sustainable domestic industry," Wang said. ☰

"Our ultimate goal is to produce hydrogen from waste plastics, biomass and coal with minimal carbon dioxide emissions. The use of these domestic resources to produce low-carbon-footprint hydrogen and chemicals can also help produce jobs through the creation of a sustainable domestic industry."

A Conversation with

Combustion Expert

Don Ferguson, Ph.D.



> **"NETL is continuing to explore options for making gas turbine engines more efficient while operating on natural gas or hydrogen."**

An unrelenting desire to discover innovations that transcend defined technological applications and the willingness to share his expertise to help in times of crisis are among the many qualities possessed by researcher Donald Ferguson, Ph.D., who works with NETL's Thermal Sciences Team. Ferguson's career spans approximately 30 years of dedicated service in research and development. During this time, he has completed fundamental research in academia (eight years) and worked in applied technologies in industry (four years). He has worked 20 years at NETL, where he continues to serve as a prolific researcher and valuable mentor. Since 2013, he has served as the principal investigator for the Pressure Gain Combustion (PGC) research project at NETL. He is a recognized expert in the fields of PGC and thermoacoustic instabilities in gas turbines.

Ferguson shared some of his insights with NETL Edge.

How did you develop your focus on gas and liquid fuel combustion, fluid dynamics and thermal sciences for advanced processes and energy applications?

Ferguson: I developed an interest in thermal sciences in undergraduate and graduate school. My master's degree focused on gas emissions from diesel engines, which are, as you could imagine, strongly dependent on combustion. This interest really took off in my doctoral studies when I specifically studied combustion for gas turbine engines.

How did your career lead you to NETL?

Ferguson: I was actually very lucky and just happened into a career at NETL. When I decided to leave industry and return to academia to pursue a doctorate degree in mechanical engineering, I stumbled upon an educational program offered by DOE. The Student Career Employment Program (SCEP) was an incredible opportunity that included financial support while working on my degree and a full-time, federal position once complete.

What do you find most rewarding about your experiences in mentoring younger generations and those considering careers in science or engineering?

Ferguson: I love the excitement and energy that students and recent graduates have. I guess I kind of feed off their energy. I have worked with a lot of really great students over the years. Their interest and excitement have helped me stay interested and look for opportunities to learn new things and work on advancing new technologies.

For many years, you've been actively engaged in your community, including search and rescue activities. What have been your most rewarding experiences in these efforts?

Ferguson: My involvement with Wilderness Search and Rescue (WiSAR) has been very rewarding. I spent the better part of 17 years very involved with WiSAR including helping to build an active search and rescue council that spanned the state of West Virginia and worked closely with the West Virginia State Police and the West Virginia Department of Homeland Security. Through this work, I have helped find numerous lost persons, which is very rewarding.

Work and family responsibilities have kept me away from WiSAR for the past few years, but I hope to one day return to this very rewarding activity. More recently, I have been involved in other volunteer opportunities. For a few years I organized a Lego robotics program at my kids' school, and I volunteered as a Cub Scout leader. For the last two years, I have been a coach for

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the West Virginia Interscholastic Cycling League, which is a mountain biking program that gets kids on bikes. The league puts on a series of races across the state for middle and high school athletes. One of the best elements of the league is that there is no “bench”; everyone gets to compete in every race. There are also lots of opportunities for kids that don’t want to race but want to pursue their own adventures in mountain biking.

How has your expertise in science and engineering benefitted the search and rescue (SAR) community and what experiences from SAR have you applied to energy research?

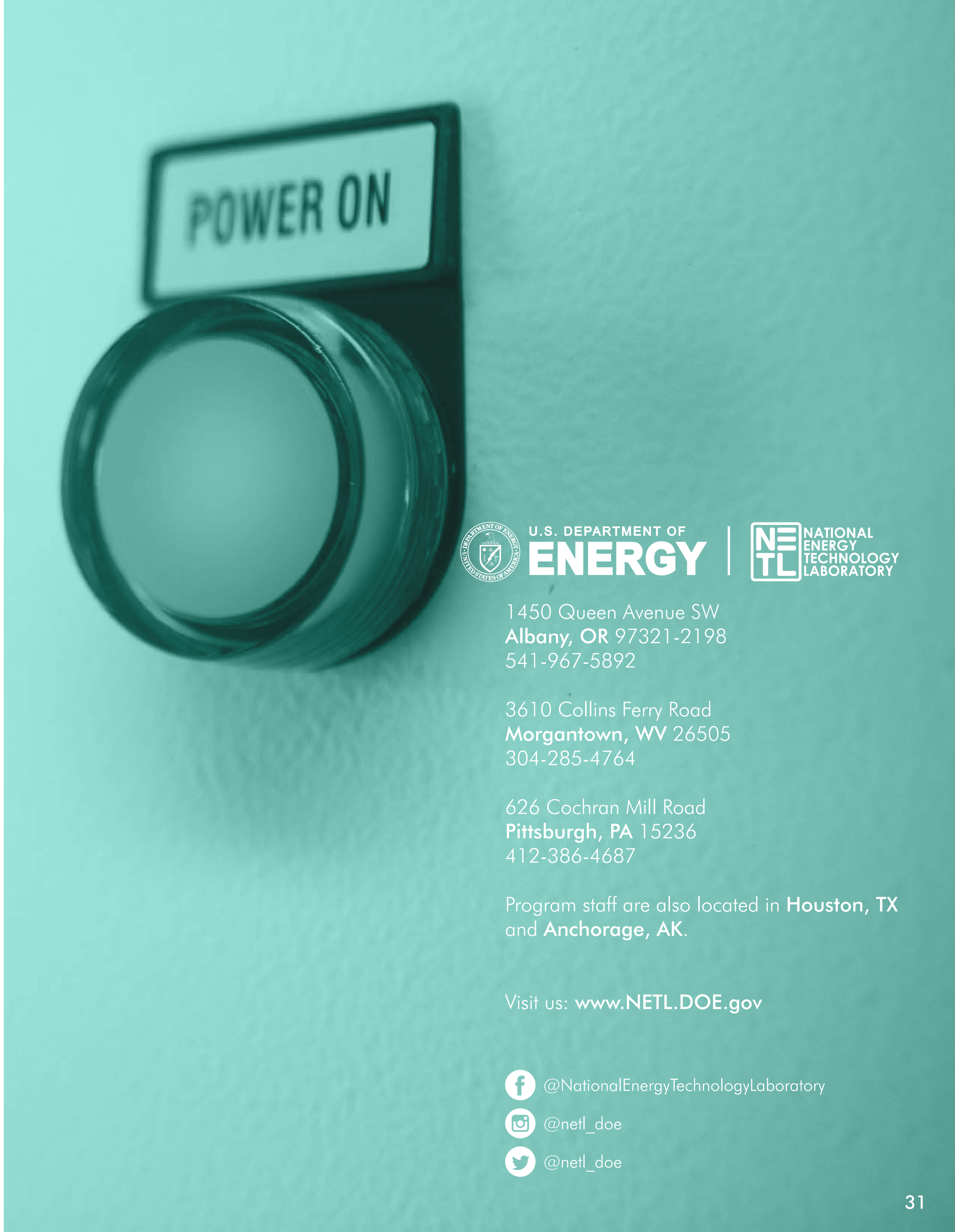
Ferguson: Actually, my science and engineering background was very beneficial to my WiSAR involvement. Beginning in 2006, I began working with several other WiSAR volunteers who had experience with Geographical Information Systems (GIS). We really pioneered the use of GIS and expanded the role of operations research (OR) in WiSAR. This combined spatial and analytical decision-making element to help guide WiSAR planners and managers in the search for lost persons. As part of this effort, I was able to teach classes around the country to volunteer and professional search and rescue workers, as well as having an opportunity to work with the National Park Service to implement some of the GIS and OR tools I helped develop.

Today, I utilize similar tools as a volunteer regional coordinator (RC) for DOE’s Office of Cybersecurity, Energy Security and Emergency Response (CESER). This is part of the Emergency Support Function 12 (ESF12) that NETL manages. As an ESF12 responder (and RC), I provide support during significant man-made and natural disasters by deploying to areas that have been heavily damaged. While deployed, I work with FEMA, State Offices of Emergency Management and public/private entities of the various energy sectors to restore services (electricity, natural gas, etc.).

What do you think the future of combustion and gas turbine technologies will look like?

Ferguson: I believe combustion will continue to play a vital role in our nation’s energy supply and industrial sector for the foreseeable future. Many processes rely on thermal energy as an input, and while there are other sources of energy none seem to be as reliable as combustion in terms of converting chemical energy to thermal energy to drive a process. Combustion, and particular gas turbine combustion, directly supports the current administration’s goal of net-zero carbon emissions from the power sector by 2035. Hydrogen is a carbon-free fuel and is readily available although it is typically locked up in some compound with other elements. Hydrogen can be extracted from these compounds, and when coupled with carbon capture, utilization and sequestration (CCUS) the process can be net-zero carbon emissions. I also think natural gas combustion, when coupled with CCUS, will continue to play an important role in de-carbonizing the energy sector.

At-scale gas turbine engines offer an efficient technology for converting chemical energy stored in fuel (hydrogen and natural gas, for example) to electrical power. While DOE’s Advanced Turbines Program has played a significant role in improving these devices, one of the best ways (in my view) to reduce carbon emissions from the power sector is to continue to improve the efficiency of gas turbine engines. The most efficient natural-gas-powered gas turbines operate around 45% efficiency; improving the simple cycle efficiency by about 5% (~50%) could result in a 10% reduction in CO_2 emissions. That is a pretty big decrease in CO_2 emissions that could reduce the demands on an accompanying CCUS process. NETL is continuing to explore options for making gas turbine engines more efficient while operating on natural gas or hydrogen. Rotating detonation combustion is one of those technologies. ≡



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Vol. 04/ Issue 02

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