NREL
Transforming ENERGY

ADVANCING GEOTHERMAL RESEARCH

2019 ACCOMPLISHMENTS REPORT

DECEMBER 2019

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Cover photo:
Drilling and well costs are two areas with the greatest potential to improve geothermal's levelized cost of electricity (LCOE). This picture shows a blow-out preventer used for well testing. *Photo courtesy of Piyush Bakane, first place winner of the Geothermal Resources Council 2018 Geothermal Photo Contest*

Steam from geothermal power plants in the distance overlooking the Salton Sea in California. *Photo courtesy of Janet Harvey, first place winner of the Geothermal Resources Council 2019 Geothermal Photo Contest*

EXECUTIVE SUMMARY

Research and development (R&D) at the National Renewable Energy Laboratory (NREL) supports the U S Department of Energy (DOE) Geothermal Technologies Office (GTO) to advance geothermal energy options today and strategically plan for tomorrow In FY19, NREL expanded its collaboration with public and private partners, demonstrated industry leadership, grew its talent base, invested in key technologies research, and increased public outreach

INDUSTRY LEADERSHIP

In FY19, NREL continued to play a pivotal leadership role in advancing GTO-specific initiatives including the *GeoVision* analysis, EGS Collab, play fairway analysis, efficient drilling, and machine learning as well as DOE initiatives including Beyond Batteries, cybersecurity, and integrated enhanced geothermal systems R&D Laboratory Program Manager Kate Young testified before the Senate Energy and Natural Resources Committee about geothermal research needs, and NREL staff are among the U S team chairing the international nonprofit Women in Geothermal NREL also partnered with GTO, Sandia National Laboratories, and Colorado School of Mines to lead a drilling efficiency workshop at the Geothermal Resources Council Annual Meeting

TOP TALENT AND CROSS-CUTTING LABORATORY CAPABILITIES

NREL attracts and recruits top talent from around the world to deliver impactful results The laboratory added seven geothermal staff, confirmed a new joint appointment with Colorado School of Mines, and leveraged laboratory capabilities including strategic analysis, scientific computing, material sciences, thermal sciences, and electronics engineering

RESEARCH AND STRATEGIC PARTNERSHIPS

NREL research partners included national laboratories, universities, and small and large companies at the vanguard of the industry NREL further leveraged GTO funding with strategic partners including DOE's Advanced Research Projects Agency-Energy, U S Bureau of Land Management (BLM), University of Utah, and private industry partners

LABORATORY INVESTMENT IN GEOTHERMAL TECHNOLOGIES RESEARCH

NREL made critical investments to expand promising geothermal research areas including lithium recovery from geothermal brines, geothermal integration at the NREL Flatirons Campus, and development of wide-bandgap oxide materials for high-temperature electronics

EXPANDED OUTREACH THROUGH PUBLICATIONS AND ENGAGEMENT

NREL researchers published 37 technical reports, conference papers, journal articles, presentations, posters and fact sheets, and expanded its reach via the website *www.nrel.gov/geothermal*, industry conferences, and social media campaigns

FY19 NATIONAL LABORATORY PARTNERS

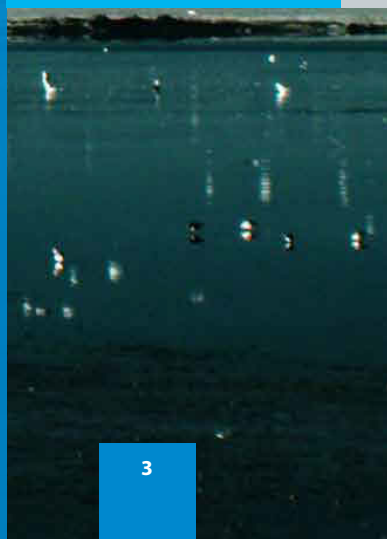
Sandia National Laboratories

Lawrence Berkeley National Laboratory

Idaho National Laboratory

National Energy Technology Laboratory

Pacific Northwest National Laboratory



LEADERSHIP HIGHLIGHTS

LANDMARK *GEOVISION* REPORT HIGHLIGHTS 60 GW OF GEOTHERMAL POTENTIAL BY 2050

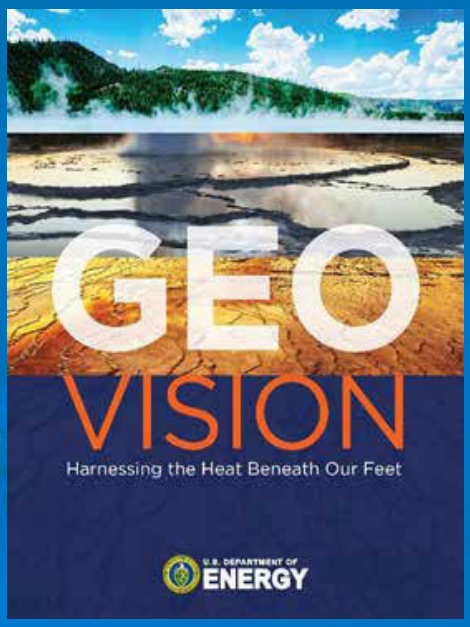
There is enormous untapped potential for geothermal energy in the United States. Making geothermal more affordable can increase our energy options for a more diverse electricity generation mix and for innovative heating and cooling solutions for all Americans.

-U.S. Secretary of Energy Rick Perry

On May 30, U S Secretary of Energy Rick Perry announced the release of *GeoVision: Harnessing the Heat Beneath our Feet,* a landmark study of potential U S geothermal growth through 2050 The announcement marked the culmination of six years of technical leadership, research, and coordination by NREL's geothermal team NREL's high-performance computing capabilities were also leveraged for report analyses

GeoVision demonstrates the significant role that geothermal could play in the U S energy sector under future scenarios By 2050, analyses showed potential for more than 60 GW of installed capacity, 17,500 district heating projects, and more than 28 million geothermal heat pumps NREL contributions included:

- Leading the Barriers Task Force analyses, identifying barriers, quantifying impact of barriers on project economics and deployment potential, and identifying potential pathways for mitigating these challenges
- Leading the Geothermal Direct-Use analyses and heating and cooling market penetration model development
- Synthesizing analyses from the multilab team in market deployment analyses for electricity and heating and cooling sector geothermal technologies
- Developing four technical reports: Impacts, Electric Sector Potential to Penetration (P2P), Barriers, and Thermal Applications
- Critical core-team support in strategy, writing, editing, and finalizing the *GeoVision* report



GeoVision report, published May 2019. *Image from DOE*

Supporting GTO in these critical areas of its mission space helps more effectively impact geothermal technology deployment, increasing the benefits to the nation

Kate Young and other geothermal experts testify in front of the U.S. Senate committee in June. *Photo from U.S. Senate Committee on Energy and Natural Resources*

LAB PROGRAM MANAGER TESTIFIES TO SENATE COMMITTEE ON ENERGY AND NATURAL RESOURCES

On June 20, Lab Program Manager Kate Young testified before the U.S. Senate Committee on Energy and Natural Resources during a hearing to examine geothermal energy development. The hearing, "Opportunities and Challenges for Advanced Geothermal Energy Development in the United States," was called by the committee following the release of the DOE *GeoVision* report. Young testified before Senate members, including Chairman Lisa Murkowski and Ranking Member Joe Manchin, discussing geothermal energy's small footprint, reliability, grid resiliency, security, and significant potential in the future energy economy. Topics included technological advances that reduce cost, including high-temperature materials and power electronics, and "geothermal anywhere" strategies and solutions to regulatory challenges.

Young joined Assistant Secretary for Energy Efficiency and Renewable Energy Daniel Simmons, State Director with the Bureau of Land Management Timothy Spisak, CEO of Fervo Energy Tim Latimer, and Ormat Vice President Paul Thomsen to provide expert testimony on advanced geothermal energy.

Underscoring the importance of this testimony, the FY20 senate appropriation bill boosts attention and funding for geothermal R&D, and several additional bills reducing regulatory timelines and boosting federal funding for geothermal research have been drafted or introduced.

"*GeoVision* does a good job of laying out the technical and non-technical barriers that have kept us from realizing geothermal's potential. And it shows that if we can address them, through policy and innovation, this resource can make a huge contribution to America's future."

-Chairman Lisa Murkowski, R-Alaska

WORLDWIDE INDUSTRY LEADERSHIP

"Equality benefits everyone by creating a stronger work force, stronger work products, stronger companies, stronger industries, and stronger economies."

-Global WING Team Member Kate Young

Geothermal Laboratory Program Manager Kate Young and Operations Manager Caity Smith are among the U.S. team selected as the new global chair of Women in Geothermal (WING), an international nonprofit organization whose mission is to promote the education, professional development, and advancement of women in the geothermal industry. The WING U.S. team includes 10 women and "WINGmen" from the geothermal industry, hailing from government, academia, and the private sector. The U.S. team will start their chairmanship at the 2020 World Geothermal Conference in Reykjavik, Iceland. This leadership opportunity provides NREL staff with greater connection to geothermal stakeholders around the world, helping advance NREL's mission and highlighting the U.S. geothermal industry.

NREL WING members including Caity Smith (second from left) and Kate Young (second from right). *Photo from Kate Young, NREL*

PARTNERING WITH INDUSTRY TO ADVANCE GEOTHERMAL DRILLING

NREL strengthened its collaborative relationship with the Geothermal Resources Council (GRC), the primary professional educational association for the international geothermal community. Key partnering activities included:

Facilitation of the first annual industry-wide conversation on drilling improvements. NREL partnered with DOE, Sandia National Laboratories, and Colorado School of Mines to organize a critical industry technical workshop on next-generation drilling focused on the use of data and data-collection tools at the October 2018 GRC Annual Meeting in Reno, Nevada. The workshop featured distinguished oil and gas drilling efficiency experts with experience at ExxonMobil, National Oilwell Varco, Haliburton, Amoco, and PetroSkills. Topics included recent trends in using digital data in drilling management, how data analytics has changed how the drilling industry operates today, and its future potential to disrupt the geothermal drilling industry. This industry sharing of knowledge is critical to improving geothermal drilling.

Researcher presentations at GRC Annual Meeting. Researchers Greg Rhodes, Kevin McCabe, Kate Young, Amanda Kolker, Alex Badgett, Dane Christensen, and Guangdong Zhu presented at the 42nd Annual GRC Annual Meeting and were published in the GRC Transactions, Vol. 43.

GRC Board leadership. In addition to year-round geothermal industry outreach and development of new research partnerships with members of the oil and gas industry, NREL Laboratory Program Manager Kate Young serves as a director on the GRC Board and chair of the communications committee.

NREL helped organize a Geothermal Drilling panel at the GRC Annual Meeting in Reno, Nevada. Panelists (left to right): Tony Pink, Fred DuPriest, John DeWardt, and J. Ford Brett.

EXPANDING NREL EXPERTISE IN RESERVOIR MANAGEMENT, DRILLING, AND HIGH-TEMPERATURE MATERIALS

NREL added seven new staff and a joint appointment to expand the breadth and depth of the laboratory's geothermal expertise in key areas including drilling, reservoir management, and materials

Dr. Amanda Kolker | Geothermal Analyst

Professional Experience
Principal Geologist, AK Geothermal, 2008–2015

Adjunct Professor, Oregon Institute of Technology 2011–2012

Gregory Rhodes | Geothermal Analyst

Professional Experience
Principal Geologist, Rhodes Geoscience 2017–2019

Senior Geologist, Ormat 2012–2017

Nicole Taverna | Geothermal Analyst

Research Experience
B.S. Geophysics, Colorado School of Mines, May 2019

Geothermal Intern, NREL, 2016–2019

Caity Smith | Operations Manager

Professional Experience
Senior Program Coordinator, East Africa Geothermal Partnership, U.S. Energy Association, 2014–2019

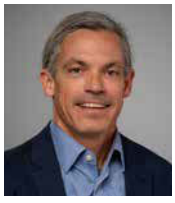
Dr. Dan Plattenberger | Postdoctoral Researcher, Material Science

Research Experience
Ph.D., Civil and Environmental Engineering, University of Virginia, July 2019

Jody Robins | Drilling Engineer

Professional Experience
Founder, VP of Drilling, Ascent Energy 2016–2019

Drilling Manager, Juneau Energy, 2014–2016



Dr. Ian Warren | Geothermal Analyst

Professional Experience
Principal Geologist, Ormat 2018–2019

Chief Geologist, U.S. Geothermal 2009–2018

Dr. Bill Eustes | Joint Appointment

Professional Experience
Associate Professor, Petroleum Engineering, Colorado School of Mines

FURTHERING NREL'S GEOTHERMAL STRATEGY: R&D HIGHLIGHTS

During the next five years, NREL will serve as a transformational leader in delivering innovative geothermal solutions to improve quality of life and move the world toward a sustainable energy future Six key research areas define NREL's geothermal research strategy

GEOTHERMAL ANYWHERE

- Enhanced geothermal systems (EGS)
- Advanced geothermal systems
- Resource assessments
- Subsurface characterization
- Induced seismicity

ADVANCED WELLS

- Reduced drilling time and costs
- Advanced well completions
- Improved wellbore integrity
- Extreme conditions

GEOTHERMAL 2.0

- Exploration and resource targeting
- Reservoir management
- Resource recovery
- Supercritical

BEYOND ELECTRICITY

- Heat (deep direct use, geothermal heat pumps)
- Molecules (lithium recovery, desalination)
- Storage
- Fuel

MARKET ACCELERATION

- Reducing regulatory timelines
- Market analysis
- New business models
- Technical assistance
- Outreach/social acceptance

GRID INTEGRATION

- Ancillary valuation
- Hybrid/flexible geothermal
- Distributed geothermal
- Grid access

Photo from iStock 1128003864

The EGS Collab team visits the Sanford Underground Research Facility at Homestake Mine in South Dakota. *Photo by Mark White, Pacific Northwest National Laboratory*

BOOSTING MODELING AND DATA MANAGEMENT FOR ENHANCED GEOTHERMAL SYSTEMS

NREL researchers Bud Johnston, Jon Weers, Nicole Taverna, and Jay Huggins supported GTO's EGS Collab project, performing modeling and data management activities among seven national laboratories and six universities. The project centers on a small-scale field site at the Sanford Underground Research Facility (SURF), where researchers perform collaborative experimental and model comparisons to deliver meso-scale stimulation and rock mechanics studies to support larger, field-scale EGS research. The project addresses critical and fundamental barriers to EGS advancement by facilitating direct collaboration between the geothermal reservoir modeling community, experimentalists, and geophysicists in developing and implementing well-field characterization and development, monitoring, and stimulation methods.

Impacts: Enhanced characterization of channelized flow paths within fractures will enable deployment of geothermal in areas without traditional hydrothermal geothermal systems.

Partners: Colorado School of Mines, Heateon

NREL performed code modifications with subsurface modeling and data management in support of circulation experiments conducted at the SURF in South Dakota. Enhanced code was used to predict tracer response and thermal breakthrough profiles associated with a range of injection rates and embedded fracture configurations. Modeling and data management accomplishments were documented in proceedings of the 44th workshop on Geothermal Reservoir Engineering at Stanford University in February 2019.

NREL data management activities also led to the creation of the NREL Data Foundry, a new secure, cloud-based environment for project collaboration among national labs, universities, and private partners. The data management platform was used by all EGS Collab participants, including seven national laboratories, six universities, and three consulting firms.

GEOTHERMAL ANYWHERE

EXPLORING POTENTIAL FOR ENHANCED GEOTHERMAL SYSTEMS AT FORGE

FORGE is a first-of-its-kind endeavor that will allow scientists to identify a replicable, commercial pathway to EGS.

NREL's Jon Weers and Jay Huggins are providing key support for the Utah Frontier Observatory for Research in Geothermal Energy (FORGE) geothermal project, a DOE-sponsored, dedicated underground field laboratory for developing, testing, and accelerating breakthroughs in EGS technologies—that is, engineering geothermal systems in areas of hot rock with low natural permeability. The FORGE field is located on the western flank of the Mineral Mountains in Beaver County, Utah.

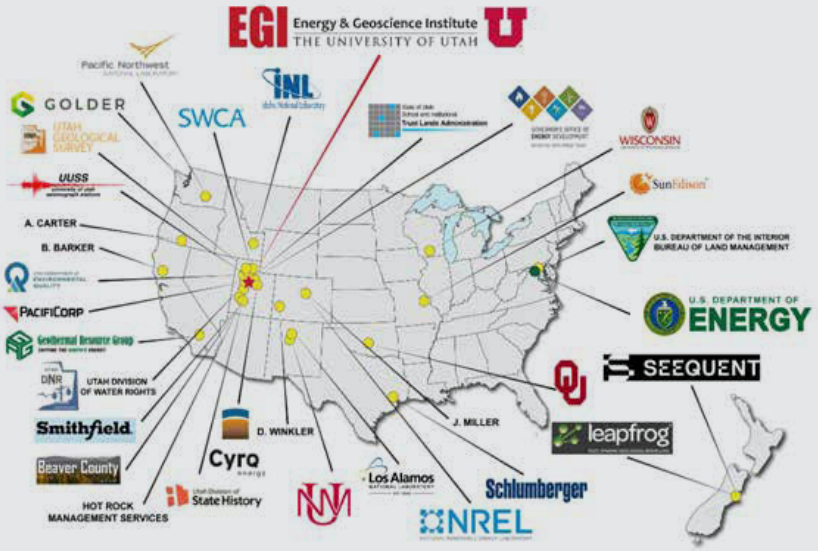
In addition to the EGS Collab project, which directly supports FORGE, NREL researchers are working with DOE and the University of Utah to organize and disseminate key project information to the geothermal scientific community. These include:

- Providing Data Foundry, a secure, cloud-based data collaboration environment geothermal experts to organize critical project data
- Linking FORGE data to DOE's Geothermal Data Repository, Data.gov, Google's Dataset search, and DOE's Office of Science and Technology
- Enabling seamless publication of data from project teams' sandboxes to the Geothermal Data Repository
- Developing a web-accessible, interactive, 3-D visualization of key FORGE data
- Showcasing FORGE data and improving data discoverability

The FORGE project is developing a functional EGS field laboratory focused on identifying a commercial pathway for EGS by improving related technologies and lowering costs. Commercially viable EGS technology could improve global geothermal energy potential by creating new geothermal opportunities where none previously existed.

Impacts: Facilitating collaboration across partners through creation of an innovative data collaboration environment; 3-D data visualization

Partner: University of Utah



NREL provides a secure, cloud-based data collaboration environment to organize and disseminate key project information across multiple FORGE project partners. *Image from DOE*

ADVANCED WELLS

DEVELOPING HIGH-TEMPERATURE SENSING ELECTRONICS FOR DOWNHOLE DRILLING AND DATA COLLECTION

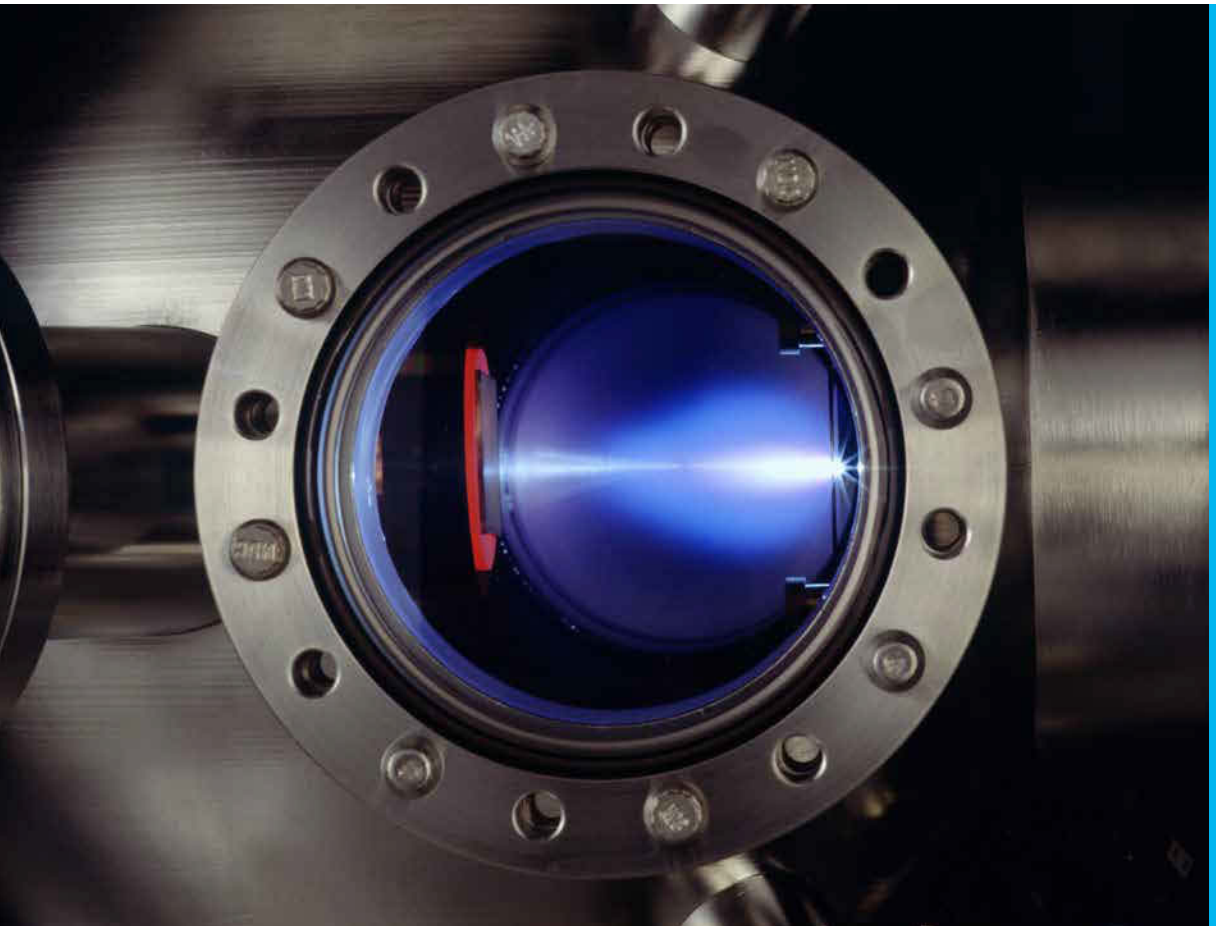
NREL researchers David Ginley and Jody Robins continued developing robust, solid-state sensor devices, using aluminum gallium nitride (AlGaN). The project, funded through the DOE Office of Technology Transitions, aims to commercialize NREL's AlGaN materials for use in high-temperature sensing electronics and apply these capabilities to geothermal applications, including downhole drilling.

Downhole drilling tools will significantly improve the accuracy of data collected as compared to the use of surface measurements, which are impaired by various boundary effects due to torque and drag alongside the drill string, torsional drill-string wrapping, and drilling dysfunctions. These effects mix with surface data, making it challenging to discern true downhole bit conditions.

The use of downhole data collection in the oil and gas industry has resulted in an overall decrease in drilling time and cost, increasing rates of penetration by 35-55%.

Impacts: **Increased downhole sensor temperature limits to facilitate geothermal drilling efficiency by incorporating NREL's AlGaN materials in high-temperature sensing electronics**

Partners: **National Oilwell Varco; Wolfspeed, a Cree Company**



Pulsed laser deposition system used for creating high-temperature superconducting films. *Photo by Jim Yost/NREL 01506.*

GEOTHERMAL 2.0

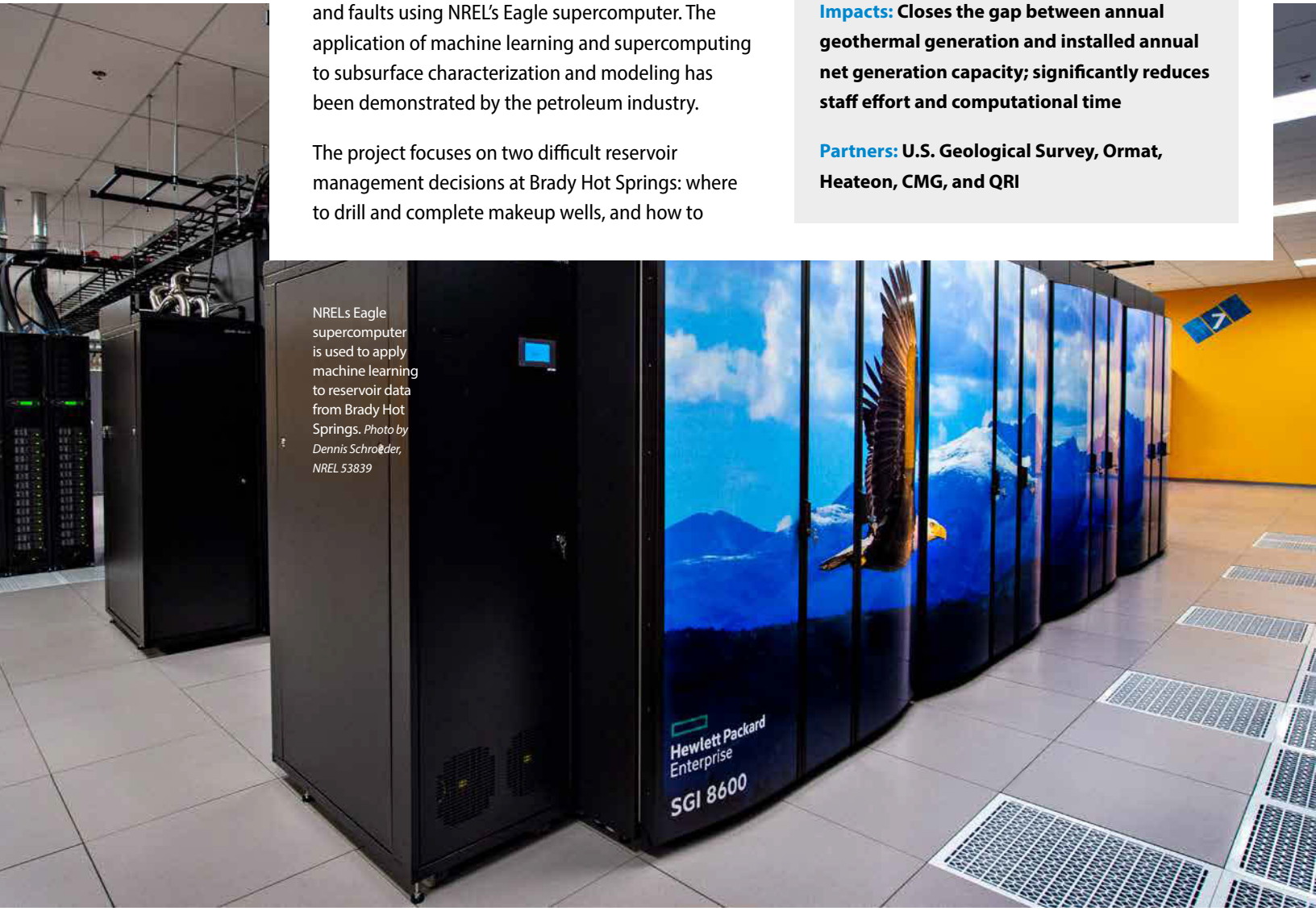
MACHINE LEARNING TO IMPROVE GEOTHERMAL RESERVOIR MANAGEMENT

NREL launched a two-year project integrating physics-based modeling and machine learning to improve geothermal reservoir management. Team members Bud Johnston, Jon Weers, Michael Martin, Caleb Phillips, and Nicole Taverna aim to improve subsurface characterization and modeling of fluid movement through geologic lithologies, fractures, and faults using NREL's Eagle supercomputer. The application of machine learning and supercomputing to subsurface characterization and modeling has been demonstrated by the petroleum industry.

The project focuses on two difficult reservoir management decisions at Brady Hot Springs: where to drill and complete makeup wells, and how to allocate injection into new and existing wells. Using machine learning, the project helps close the gap between annual geothermal generation and installed annual net generation capacity, and significantly reduces staff effort and computational time.

Impacts: **Closes the gap between annual geothermal generation and installed annual net generation capacity; significantly reduces staff effort and computational time**

Partners: **U.S. Geological Survey, Ormat, Heateon, CMG, and QRI**



NRELs Eagle supercomputer is used to apply machine learning to reservoir data from Brady Hot Springs. *Photo by Dennis Schroeder, NREL 53839*

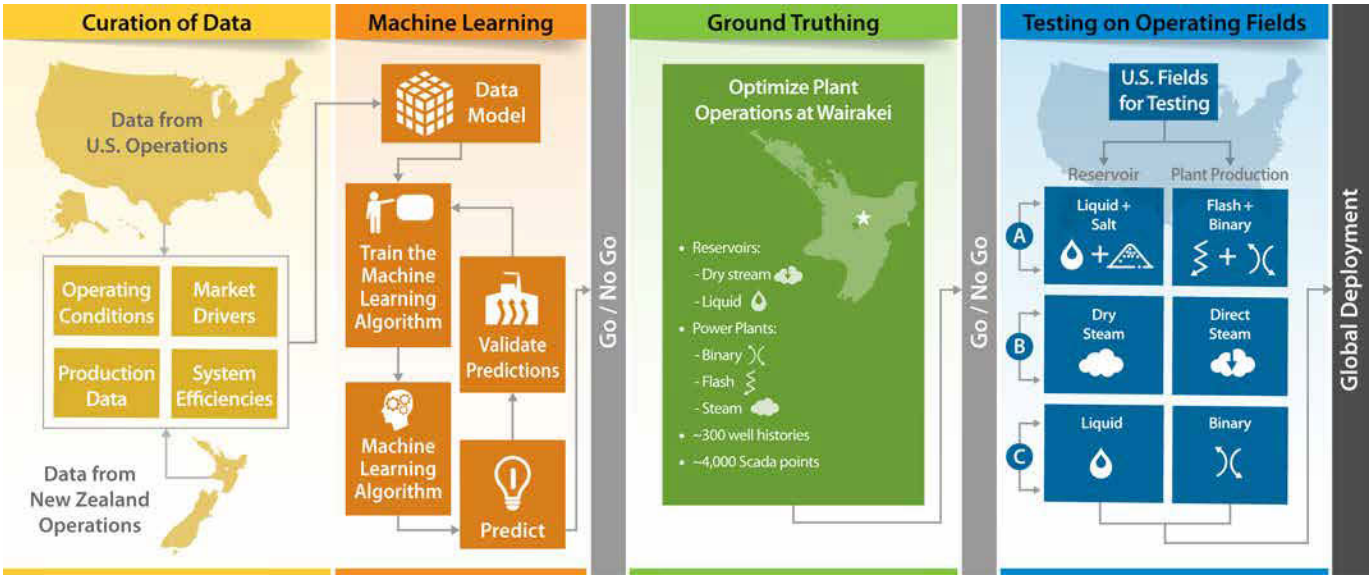
INTERNATIONAL PARTNERSHIP APPLYING MACHINE LEARNING TO A "TREASURE TROVE OF DATA" FROM NEW ZEALAND

NREL partnered with the New Zealand company Upflow in FY19 to implement the *Geothermal Operational Optimization with Machine Learning* (GOOML) project, supporting a new international collaborative agreement between DOE and New Zealand's Energy Efficiency and Conservation Authority. The project team, including Jon Weers, Nicole Taverna, and Michael Rossol, are applying machine learning to data from New Zealand's massive Wairakei geothermal field. NREL Principal Investigator Jon Weers describes Wairakei's records as "a treasure trove of data," as they offer decades of data from hundreds of wells and multiple power generation facilities, including steam, flash, and binary generators.

The GOOML project is creating "digital twin" system models of geothermal fields and applying machine learning analysis of large geothermal operational data sets from leading U.S. and New Zealand generators. Findings from the models will significantly improve overall operations through optimization of daily processes, scheduling of critical asset maintenance, and prediction and detection of potential trouble events. Geothermal operators can use the technology to achieve a step change in the availability and efficiency of geothermal operations without drilling new wells or constructing new plants. This can reduce the levelized cost of electricity for existing and future geothermal installations and increase the economic competitiveness of geothermal.

Impacts: **Optimized reservoir availability and efficiency to reduce the levelized cost of electricity from geothermal and increase its economic competitiveness**

Partners: **New Zealand Energy Efficiency and Conservation Authority, Upflow New Zealand, Contact, Ngati Tuwharetoa Geothermal Assets, Ormat, FSS**



The GOOML project includes data gathering and curation, the application of machine learning, "ground truthing" at the New Zealand plant, and the deployment of key learnings at U.S. sites.
Illustration by Al Hicks, NREL

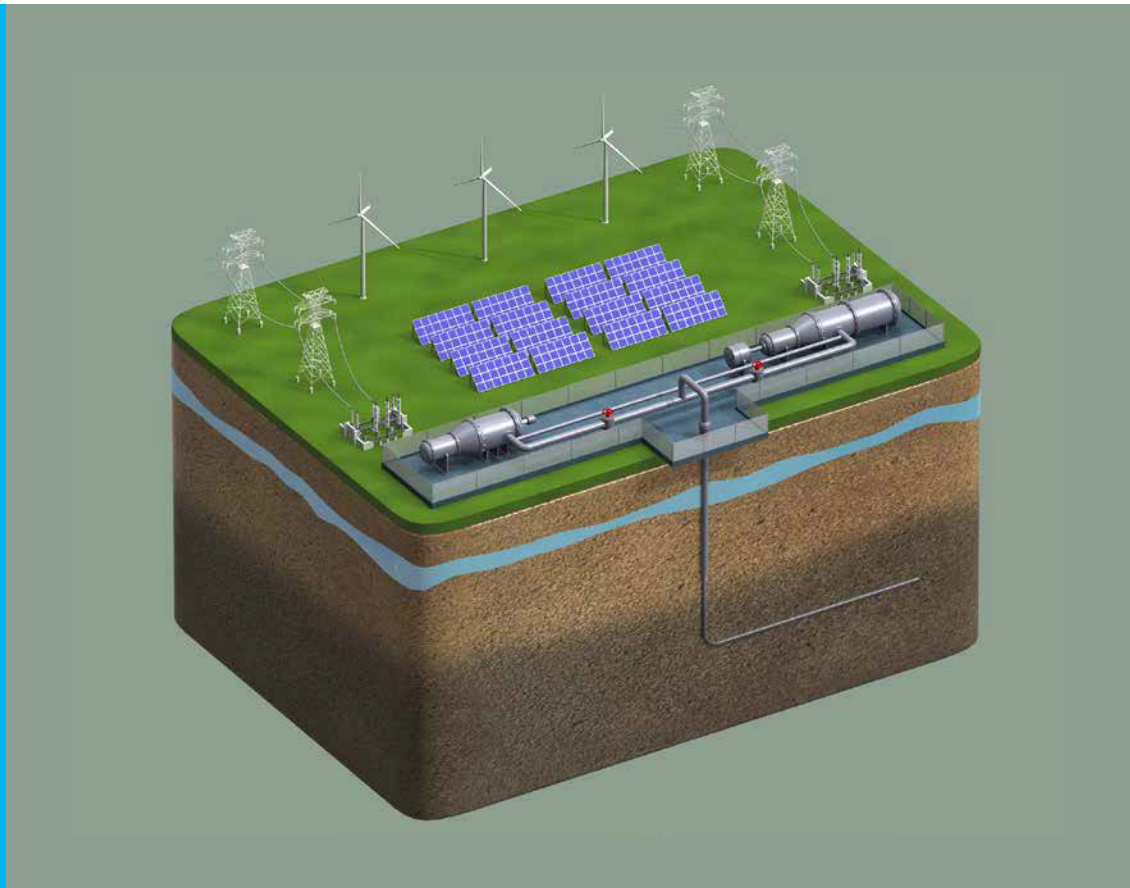
BEYOND ELECTRICITY

USING COMPRESSED GAS TO STORE ENERGY IN DEPLETED GAS WELLS

NREL researcher Chad Augustine developed an alternative compressed air energy storage (GeoCAES) technology that uses depleted unconventional gas wells for subsurface thermal energy storage. This technology could enable low-cost, widespread, gigawatt-scalable energy storage to increase grid stability and penetration of intermittent renewables. Conventional compressed-air energy storage uses excess electricity to compress air into underground salt caverns. When electrical demand grows, this energy can be released through a turbine at the surface to provide electricity. This technology is cost-effective, but few locations possess necessary salt caverns. The project is exploring the use of a more common feature—depleted unconventional shale gas wells. The project also studied storing waste heat from the compression process underground to improve overall efficiency. A patent application was submitted for the concept in FY19.

Impacts: **Safe, lower-cost, widespread, gigawatt-scalable energy storage technology to increase grid stability and enable increased penetration of intermittent renewables**

Partner: **Dresser-Rand**



GeoCAES investigates the use of underground depleted gas wells for compressed gas energy storage. *Image by Besiki Kazaishvili, NREL*

BEYOND ELECTRICITY

TEAMING GEOTHERMAL AND CSP SHOWS PROMISING ECONOMIC POTENTIAL FOR SEASONAL GRID ENERGY STORAGE AND DISPATCHABILITY

Hybridizing geothermal subsurface storage with solar heat shows promising economic potential in providing valuable seasonal grid energy storage.

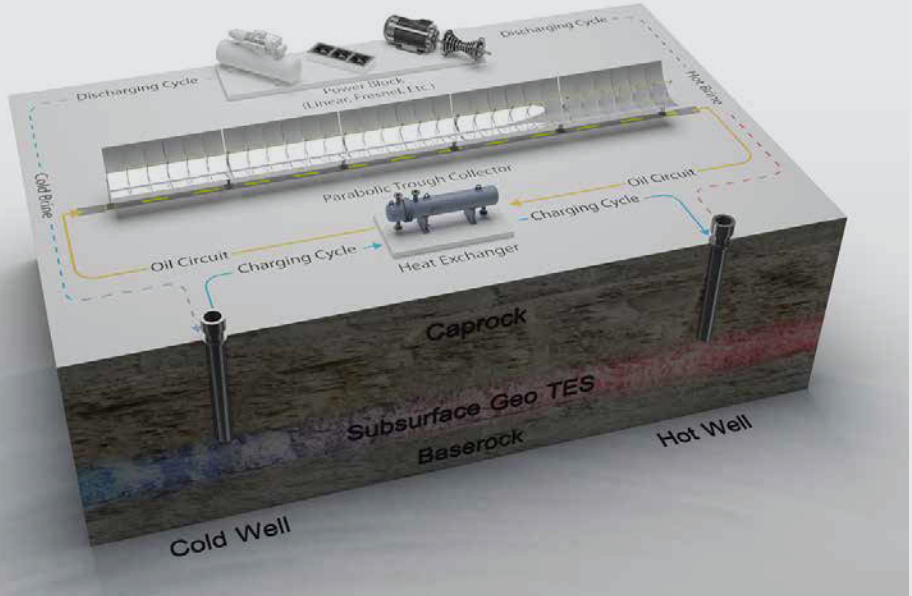
As increasing amounts of intermittent renewable energy sources, such as wind and solar, are added to the electric grid, more dispatchable power sources are required to closely follow electric load to maintain grid stability. Geothermal energy, which consistently produces power independent of the time of day or weather conditions, can help provide this dispatchability. In the *Flexible Geothermal Power Generation Utilizing Geologic Thermal Energy Storage* project, a team including NREL's Guangdong Zhu, Prashant Sharan, and Josh McTigue, as well as Idaho National Laboratory, the University of Utah, and two private companies studied the feasibility of coupling a geothermal power plant with a concentrating solar power (CSP) system. Such geo-solar integration optimization could help maximize the value of geothermal plant dispatchability that would operate more efficiently and economically while adjusting to fluctuations in demand.

The project investigated the storage of heat from CSP systems in a subsurface geological reservoir. Solar heat would increase the water temperature in the reservoir, enhancing geothermal power plant performance and efficiency. Such a pairing of energy storage with a power plant could provide seasonal storage and dispatchability as a service to the grid. Analyses were also conducted analyzing the storage of solar thermal heat in oil and gas wells.

A technical report summarizing the findings was co-authored by NREL researchers and published by Idaho National Laboratory in May 2019.

Impacts: **Combining existing solar with geothermal and/or conventional oil and gas reservoirs is a novel way to create cost-effective seasonal heat storage and dispatchable electrical generating capacity when other renewable energy is not available to meet demand**

Partners: **Idaho National Laboratory, University of Utah, Enhanced Production Inc., Kitzworks LLC**



NREL is investigating the feasibility of coupling geothermal power plants with concentrated solar power systems. *Image by Joshua Bauer, NREL*

BEYOND ELECTRICITY

EXPLORING GEOTHERMAL HEAT FOR TURBINE INLET COOLING IN EAST TEXAS

Low-temperature geothermal heat offers a new opportunity for combined-cycle plants to boost compressor performance.

NREL's Craig Turchi is exploring the feasibility of harnessing low-temperature geothermal heat for large-scale thermal projects. In particular, the *Deep Direct Use for Turbine Inlet Cooling in East Texas* project examined the potential for geothermal heat integration at natural gas power plants in East Texas.

NREL authored a feasibility study for use of absorption chillers and geothermal heat to provide turbine inlet cooling on a natural gas combined-cycle power plant, a new opportunity for combined cycle plant owner/operators in hot, humid regions with underlying low-temperature geothermal resources. Natural gas power plants lose power and efficiency during hot afternoons, so turbine inlet cooling is used to precool the air drawn into the turbine's compressor section to boost performance. The project studied the use of geothermal resources to drive absorption chillers for turbine inlet cooling.

In the final year of the project, NREL developed a performance and cost model for a geothermal-heat absorption chiller system with thermal energy storage. This included estimating expected net present value for a range of system assumptions to provide a parametric assessment of potential project economics. A sensitivity analysis identified variables of greatest influence, for example, geothermal resource temperature, heat rate benefit from inlet cooling, well drilling/completion costs, and local climate.

The research encourages power plant operators to evaluate their resource in light of the study's documented potential benefits to plant operations.

Impacts: **Opportunity for increased natural gas power plant compressor efficiency using geothermal-driven absorption coolers**

Partner: **Eastman Chemical, EPRI, TAS Energy, Southern Methodist University**

BEYOND ELECTRICITY

LEVERAGING LOW-TEMPERATURE GEOTHERMAL RESOURCES FOR DESALINATION

NREL and partner researchers at the Colorado School of Mines, University of California Riverside, and Ormat Technologies completed a multiyear project applying underused low-temperature geothermal resources to desalinate otherwise nonpotable water. Applied in the right locations, thermal desalination could mean economic viability for water treatment.

Thermal desalination technologies such as membrane distillation are generally costlier and more energy intensive than reverse-osmosis desalination. To produce high-quality water from geothermal brines at lower cost than traditional thermal distillation, the project modeled the use of untapped or residual heat in geothermal resources for the membrane distillation heat source and explored coatings to protect and improve membrane distillation by minimizing scale formation.

Project activities included:

- Demonstrating the integration of membrane distillation with geothermal energy
- Testing and evaluating antiscaling and/or antifouling coatings applied to commercial membranes
- Estimating costs of product water based on membrane performance and a sensitivity analysis to the cost of geothermal heat
- Describing and quantifying applications beneficial to the geothermal industry.

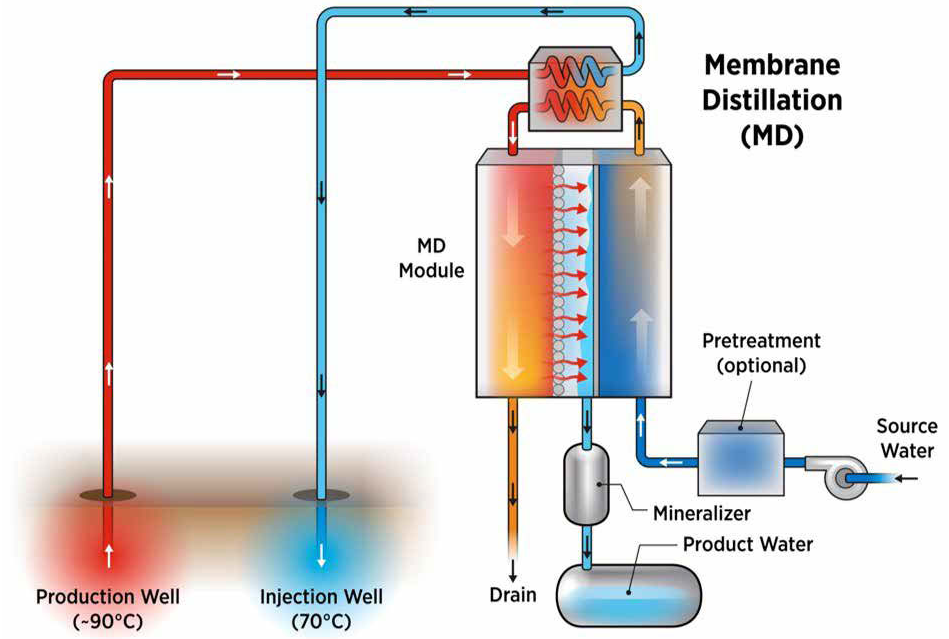
A journal article is planned in FY20.

Impacts: Development of low-cost desalination of non-potable geothermal brines using residual geothermal heat

Partners: Sandia National Laboratory, Colorado School of Mines, University of California Riverside, Ormat, GE Power & Water

"Water scarcity is a growing problem throughout the world. The ability to apply renewable energy solutions is key to a sustainable water future."

-Craig Turchi, principal engineer



NREL, Colorado School of Mines, UCLA, and Ormat partnered to model the use of geothermal heat for membrane distillation. *Image by Al Hicks, NREL*

MARKET ACCELERATION

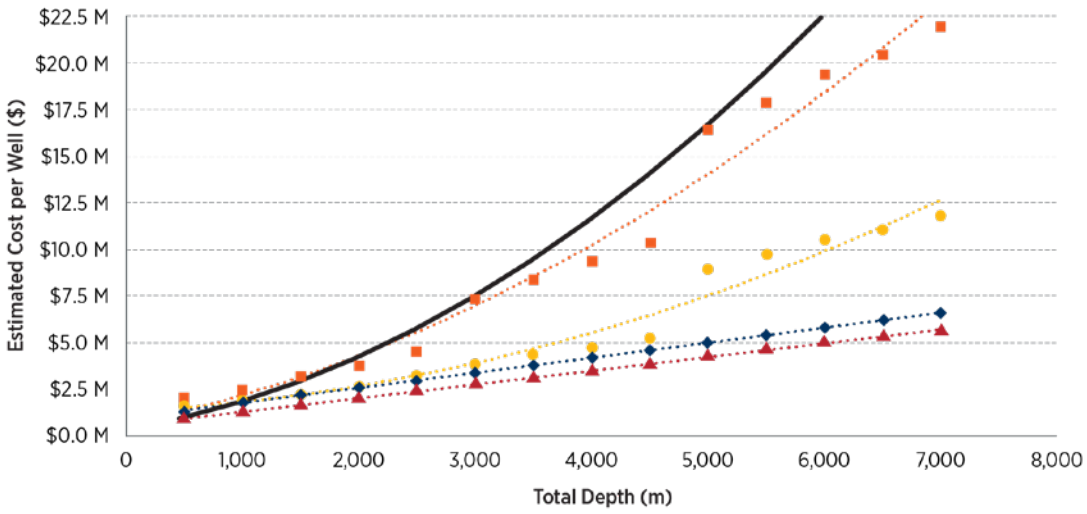
RAISING THE PROFILE OF GETEM TO CALCULATE GEOTHERMAL TECHNOLOGIES' PERFORMANCE AND COSTS

NREL researchers Chad Augustine and Greg Rhodes support and develop the Geothermal Electricity Technology Evaluation Model (GETEM), a software tool used for calculating the performance and cost of geothermal technologies, providing supply curve analyses, assessing the current economic feasibility and levelized cost of electricity (LCOE) of geothermal systems, and evaluating the potential impact of advanced geothermal technologies. GETEM can be used to analyze and evaluate the state of existing technologies and estimate the cost of certain technologies in improved scenarios.

NREL continued to provide technical support to GTO in performing analyses with GETEM in FY19. The GETEM team also continued to transition the tool from an Excel platform to NREL's System Advisor Model (SAM), adding more functionality to the SAM version, including the ability to automatically estimate plant cost. Annual updates were performed in both Excel and SAM versions. NREL is also working in concert with the Office of Energy Efficiency and Renewable Energy and GTO to assess the true or "net" value to the grid using GETEM as part of DOE's larger "Beyond LCOE" initiative, as described in the following section. GETEM also featured prominently in the *GeoVision Analysis Supporting Task Force Report: Electric Sector Potential to Penetration*.

Impacts: Allows for estimations of LCOE for geothermal at individual locations, development of supply curves for market modeling, and measurement of GTO RD&D impacts

Partner: Idaho National Laboratory



GETEM was used extensively in GeoVision cost forecasting. *Image from DOE*

MARKET ACCELERATION

BEYOND LCOE QUANTIFIES THE BROADER BENEFITS OF GEOTHERMAL

There are grid benefits from geothermal energy beyond what is reflected in the levelized cost of electricity (LCOE), a metric commonly used to compare technologies and inform investment and R&D decisions. These include the value of capacity, ancillary services, grid stability, demand response, and avoided costs, among others. As the penetration of intermittent renewable energy resources such as wind and solar increases, so does the relative net value of geothermal projects to grid operations, making LCOE alone an incomplete indicator of a project's true value.

To address this need, NREL's Chad Augustine and Greg Rhodes are part of a multilab team supporting the *Beyond LCOE* project in developing and applying a framework to enable estimation of the broader set of costs and values associated with geothermal and other projects. Partners include Idaho National Laboratory, Pacific Northwest National Laboratory, Lawrence Berkeley National Laboratory, and National Energy Technology Laboratory.

During FY19, the *Beyond LCOE* team compiled geothermal flexibility characteristics for review by the full multilab team.

Impacts: Increased stakeholder awareness about geothermal energy's grid stability and resilience benefits; transforming the marketability of geothermal as a dispatchable competitor to natural gas

Partners: Idaho National Laboratory, Pacific Northwest National Laboratory, Lawrence Berkeley National Laboratory, National Energy Technology Laboratory

As the penetration of intermittent renewable energy resources such as wind and solar increases, so does the relative net value of geothermal projects to grid operations changes.

Grid benefits to geothermal energy include capacity, ancillary services, grid stability, demand response, and avoided costs. *Photo by Dennis Schroeder, NREL 46264*

MARKET ACCELERATION

GEOPHIRES 2.0 SOFTWARE FOR ENHANCED TECHNO-ECONOMIC ANALYSIS OF GEOTHERMAL HEAT AND ELECTRICITY GENERATION

Researchers Koenraad Beckers and Kevin McCabe led the release of GeoPHIRES 2.0, a simulation tool for techno-economic analysis of geothermal heat and electricity generation. The software incorporates reservoir, wellbore, and surface plant models and an integrated economic model to estimate capital and O&M costs, lifetime energy production, and overall levelized costs of electricity and heat for plant operators.

Software upgrades included coupling GeoPHIRES with Lawrence Berkeley National Laboratory's TOUGH2 software to provide a more advanced reservoir model. Other advances included updated, built-in cost correlations, enhancements to the built-in wellbore simulator, conversion of the programming language to Python, and making the code open source.

Impacts: **Improved reservoir modeling, ease of use and availability of GEOPHIRES to the public for understanding techno-economic potential of geothermal heat and electricity projects.**

Partners: **Cornell University, Lawrence Berkeley National Laboratory**

The software has been used by more than half a dozen GTO-funded Deep Direct-Use and Beyond Batteries FOA research teams, including:

- NREL research on geothermal heat for absorption chiller turbine inlet cooling
- Cornell University research examining geothermal heat for a campus loop system
- Portland State University evaluation of thermal energy storage to heat and cool critical infrastructure including the Oregon Health & Science University hospital.

Other FY19 highlights included publication of *GEOPHIRES v2.0: Updated Geothermal Techno-Economic Simulation Tool,* featuring a case study and model documentation in *Geothermal Energy*. Future goals include advancement beyond the research stage to collaboration with private industry partners.

The Milgro Nurseries greenhouse near New Castle, Utah, is one of the approximately 40 greenhouses nationwide that benefit from the direct use of geothermal heat.
Photo by Robert Blackett, NREL 13981

MARKET ACCELERATION

EXPLORING DATA SHARING AND COLLABORATION WITH MINING INDUSTRY PARTNERS

NREL's Aaron Levine initiated new research and analysis on potential collaborations between the geothermal and mining industries that could lead to the discovery and development of additional hydrothermal resources. Project objectives include:

- Determining the usefulness of mining data toward the discovery of additional hydrothermal resources
- Evaluating potential geothermal cost reductions from leveraging mining data or an existing mine site
- Identifying potential collaborations between the mining and geothermal industry stakeholders.

FY19 activities included an extensive literature review of relevant research and analysis, identification of previous or proposed geothermal projects that leveraged mining industry data or sought to co-locate a geothermal and mining project, collection of mining industry data to determine its suitability for geothermal resource discovery, and preliminary techno-economic analysis.

Project Objectives: Determining usefulness of mining data toward the discovery of additional hydrothermal resources and geothermal cost reductions; identifying potential collaborations between mining and geothermal industry stakeholders

The Florida Canyon Mine in Nevada hosts a small-scale geothermal system capable of generating electricity.
Photo from GeoMine

GRID INTEGRATION

GEOTHERMAL SYSTEMS FOR COLD-CLIMATE ZERO ENERGY COMMUNITIES

Geothermal can enable cost-effective transition to zero energy in cold-climate communities, with a total potential of at least 1.5 quads, to displace 25% of residential primary energy.

In northern climates, building thermal needs are higher, and solar resources are typically lower-performing than in the rest of the United States, making business practices for zero energy development relatively more costly. Within the *Exploring the Role of Geothermal in Cold-Climate Zero Energy Communities* project, investigators Dane Christensen, Kevin McCabe, William Becker, Dylan Cutler, Jeff Maguire, Samantha Reese, and Andrew Speake analyzed the feasibility and value of integrating geothermal resources with energy storage and flexible, energy-efficient buildings, improved asset utilization, and reduction of grid dependence.

The project included a techno-economic analysis of small-scale geothermal systems producing heat and electricity, and relevant energy storage if required, to serve a cold-climate, zero energy community. The techno-economic analysis evaluated cost/benefit tradeoffs, such as drilling cost or generator unit cost limits to achieve economic viability for zero energy communities. Under certain conditions, community-scale geothermal resources are quite competitive with today's grid tariffs and with photovoltaics (PV), showing an LCOE within $0.01/kWh before consideration of important grid modernization factors such as resiliency and reliability.

The work also identified that geothermal-produced electric power will be self-consumed on the site at a much higher level, compared with solar PV generation that achieves the same annual energy output. This implies that solutions including geothermal production can deliver renewable energy without infrastructure upgrades and operational challenges that are often considered by utilities when transitioning to high-PV or high-wind generation mixes. Improved economics from reductions in infrastructure were not evaluated but may provide additional economic benefits.

Finally, the work studied thermal energy distribution from the geothermal well to the district's buildings, to support thermal loads in the cold climate. In certain tariff scenarios, thermal energy distribution was found to be cost-effective, while thermal storage was found to be economically viable in some cases.

Results were presented at the GRC Annual Meeting. The analysis was complex and site-dependent, and the techno-economic design method developed for this project may evolve into a future tool for land developers, policymakers, and technology manufacturers.

Impacts: Demonstrated community-scale geothermal resources can be competitive with today's grid tariffs and with PV; informs strategic decisions pertaining to sustainable community development, infrastructure transition, and future building and geothermal technology development

NREL researchers analyzed integration of geothermal resources with energy storage to achieve economic viability in zero energy cold-weather communities. *Photo by Craig Christensen, NREL 12948*

GRID INTEGRATION

ASSESSING CYBERSECURITY RISKS FOR GEOTHERMAL RESOURCES

Geothermal researchers Ian Warren and Kate Young partnered with NREL's Cyber-Physical Systems Group, Lawrence Berkeley National Lab, and KitzWorks LLC to evaluate and strategize around potential cybersecurity threats to geothermal resources in the United States, showcasing NREL's leadership in advancing geothermal research and cybersecurity.

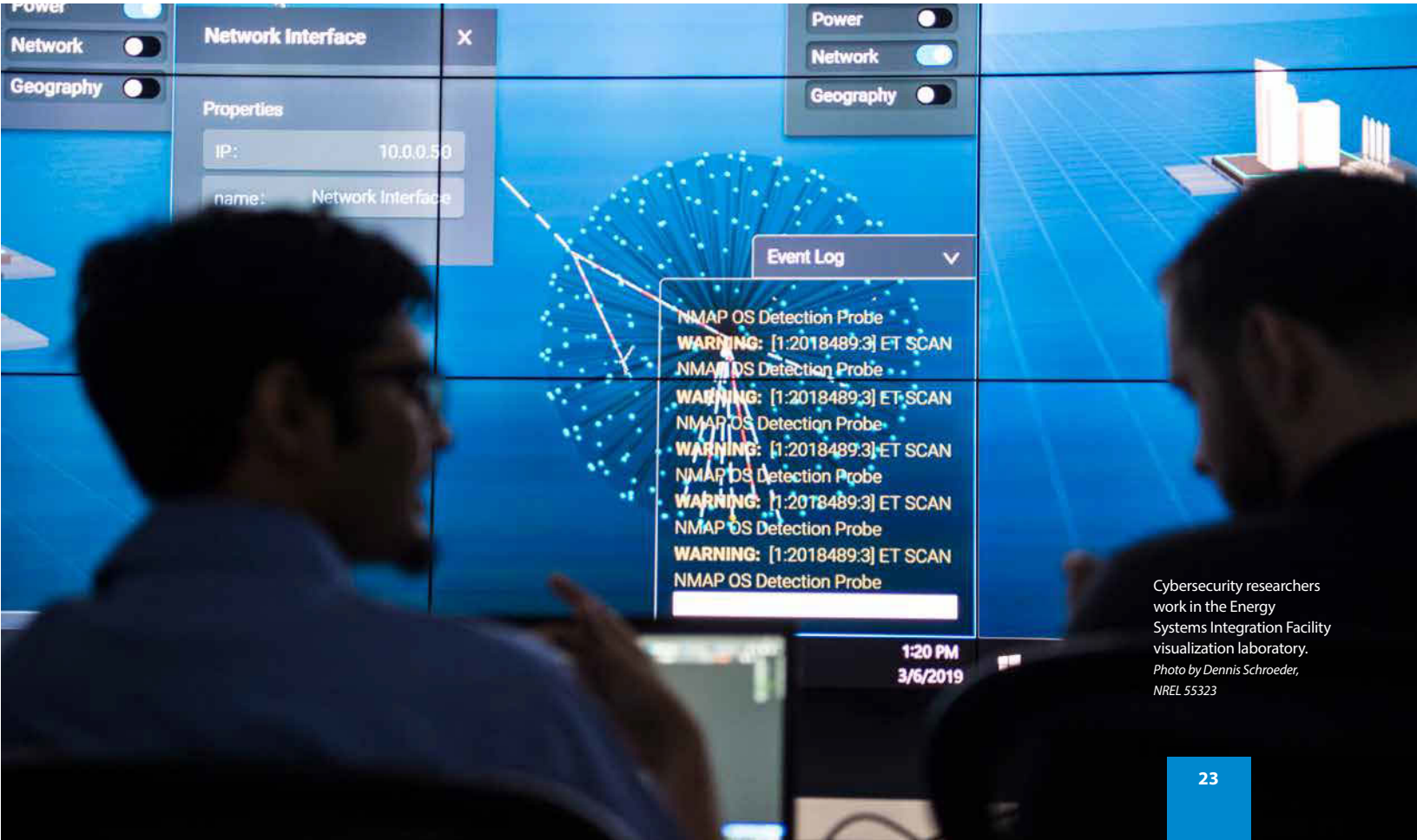
Cybersecurity assessment objectives include:

- Identifying existing best practices and attributes that provide enhanced geothermal cyber-physical security
- Recognizing unique features and systems that may require further research and guidance to improve security of assets and operations
- Summarizing insights into actions for both DOE and industry

The Cyber-Physical Systems Group will publish a report on the group's findings, to be delivered to GTO in early FY20.

Impacts: Greater understanding of cybersecurity risks, allowing the U.S. to plan for increased security for the national electricity grid

Partners: KitzWorks LLC, Lawrence Berkeley National Lab



Cybersecurity researchers work in the Energy Systems Integration Facility visualization laboratory. *Photo by Dennis Schroeder, NREL 55323*

STRATEGIC PARTNERSHIPS

Photo from iStock 1040595482

RePED 250: INDUSTRY-DISRUPTING DRILL TECHNOLOGY

NREL researchers are working to advance high-temperature geothermal drilling. Currently, geothermal drilling averages 125 feet per day through hard rock and crystalline formations, making it time-consuming and expensive compared to oil and gas industry drilling. However, Tetra Corporation has patents for low-temperature oil and gas drilling that increases rates in very hard, abrasive, sandstone formations.

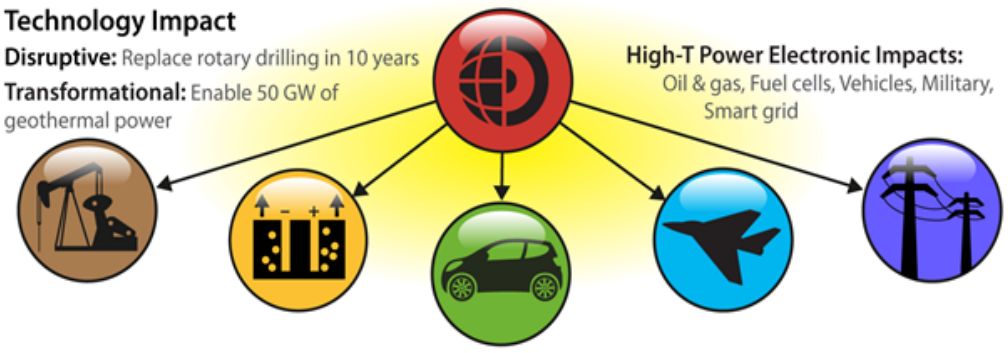
Within the RePED 250 project, NREL's Jody Robins, Kate Young, Lee Jay Fingersh, and Dave Ginley are working to adapt Tetra's drilling patent technology to the hotter, harder, crystalline rock found in geothermal wells through development of high-temperature power electronics including alternators, capacitors, and high-voltage, pulsed-power switches. If successful, the technology is expected to disrupt the global drilling industry, replacing traditional drilling technologies within 10 years of commercialization. The technology would increase drilling rates tenfold, reduce geothermal well drilling costs by 75%, and cut development timelines, significantly increasing the market competitiveness of geothermal power. Competitive market modeling shows the potential for an additional 50 GW of geothermal deployed in the U.S. because of cost and time improvements from this new technology.

High-temperature power electronics developed through this research will also have immediate applicability in many industries including petroleum, fuel cells, vehicles, smart grid, and the military.

The technology would increase drilling rates tenfold, reducing geothermal well drilling costs by 75%.

Key Impacts: Fourfold increase in drilling energy efficiency, tenfold increase in drilling speed, and at one-fourth of the cost

Partners: Tetra Innovation Institute, TPL, Inc., University of New Mexico



High-temperature power electronics research aims to adapt new oil and gas industry drilling technology to hotter, harder crystalline rock found in geothermal wells. *Image by Al Hicks, NREL*

Jose Rios from the BLM Nevada State Office inspects an abandoned well at San Emidio geothermal plant, U.S. Geothermal, Nevada. *Photo by Dennis Schroeder, NREL 48105*

EXPANDED SUPPORT FOR THE BUREAU OF LAND MANAGEMENT GEOTHERMAL PROGRAM

NREL deepened its partnership with the U.S. Bureau of Land Management (BLM) to support its geothermal program management activities. For the fourth year in a row, NREL has provided BLM geothermal program technical and regulatory analysis assistance in implementing its activities. In FY19, NREL developed tools for geothermal land and royalty calculations, analysis of environmental impacts of geothermal operations on BLM land, ongoing regulatory analysis, and continued work on field validation of BLM wells. Activities included:

- Verifying production of geothermal wells within BLM territory
- Development of a series of training modules for BLM staff
- Creation of multilayer regional geothermal resource maps
- Technical support on geothermal operations including leasing, permitting, and bonding.

Additional rounds of funding awarded this year expand an interagency agreement in place since 2015. Project team members include Amanda Kolker, Jeff Cook, Kate Young, Jody Robins, Ian Warren, Aaron Levine, and Nicole Taverna.

Impacts: Supports the streamlining of geothermal resource development throughout the lifecycle of geothermal project operations across 245 million acres of public lands

DATA FOUNDRY OFFERS SECURE, CLOUD-BASED COLLABORATION

For the past year and a half, NREL's Jon Weers has led the development of Data Foundry, a secure cloud-based environment for project collaboration among national labs, universities, and private partners. The platform has garnered praise from DOE for delivering unprecedented ease of collaboration.

Data Foundry eliminates a long-standing hurdle in laboratory project collaboration. Research projects are implemented in partnership with different universities and corporations. Shared data is often proprietary and needs to be shared in adherence to both DOE and NREL cybersecurity guidelines for handling of sensitive data.

Previously, the inconvenient workaround was to create a national laboratory login for each collaborating partner—a process that could delay a project by weeks, especially when dozens of collaborators are involved. Data Foundry meets cybersecurity needs while allowing collaborators to login using, for example, a Google account and two-factor authentication.

Data Foundry is built in NREL's secure cloud environment and offers:

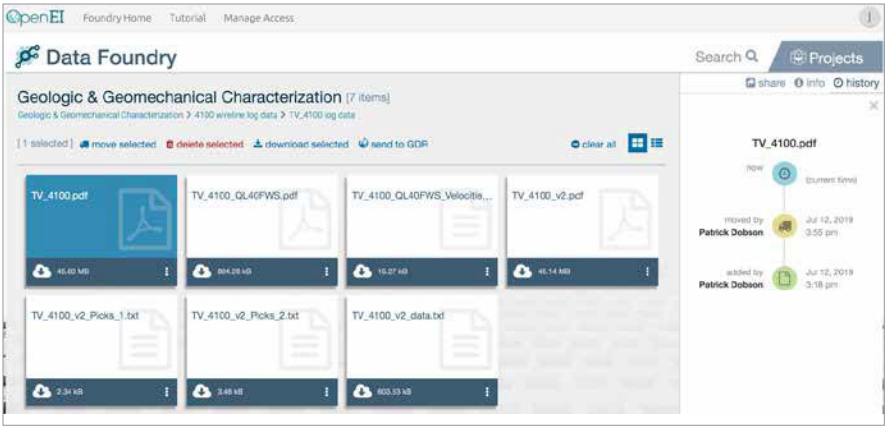
- A secure data collaboration environment that is equally accessible from multiple national laboratories and other agencies
- A data management process and the ability to quarantine data for access by smaller user subsets
- The ability to publish data sets directly to DOE's Geothermal Data Repository
- Infinitely scalable, elastic drives for limitless, secure data storage.

NREL team members supporting the Data Foundry project include Nicole Taverna, Jay Huggins, Aaron Vimont, and Thomas King.

Impacts: Unprecedented ease of collaboration among national laboratories, federal agencies, universities, and private sector partners through a secure, cloud-based environment.

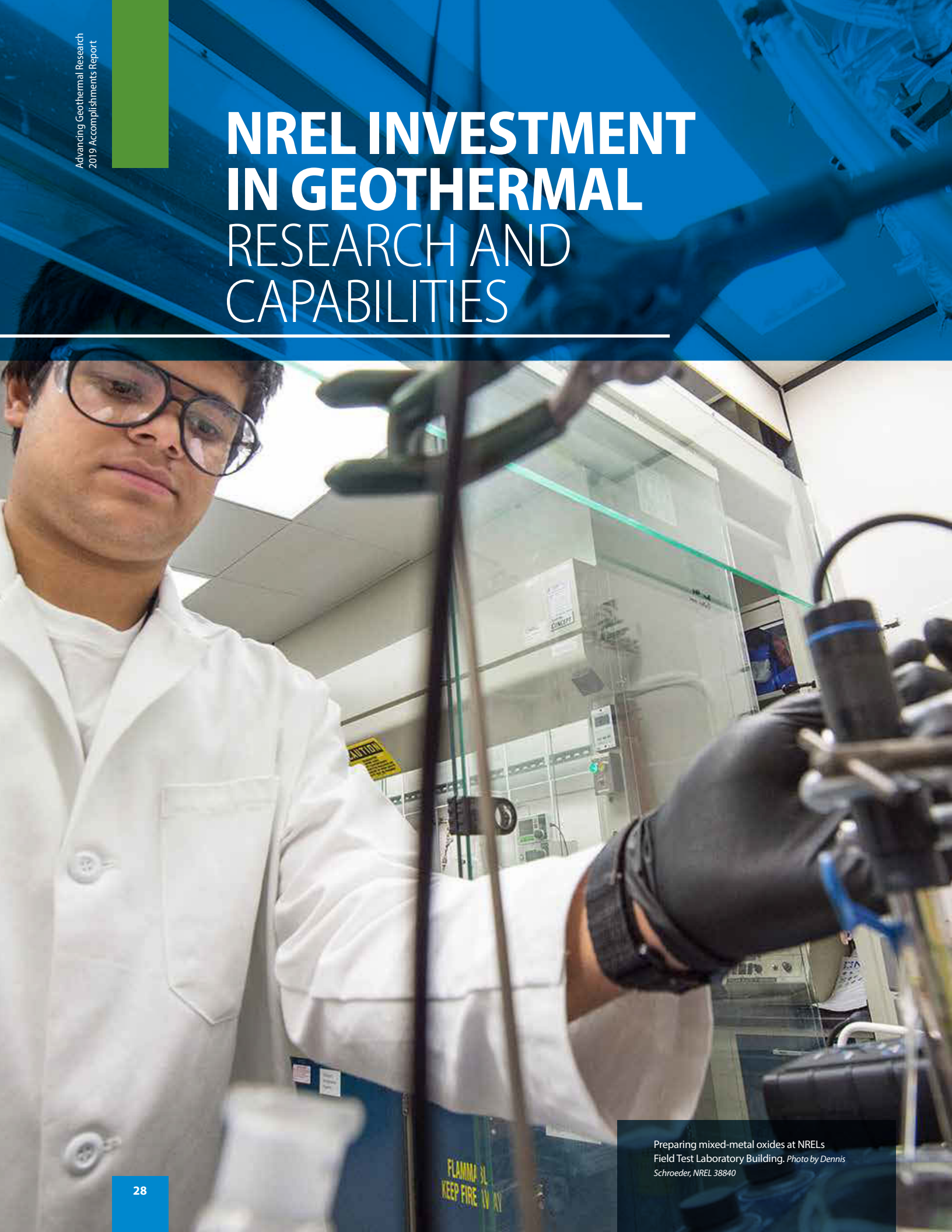
"Your work has enabled so much collaboration across the GTO portfolio."

-Lauren Boyd, enhanced geothermal systems program manager, GTO



Data Foundry enables infinitely scalable storage, direct linkage to the DOE Geothermal Data Repository, and secure project collaboration among multiple labs, universities, and private partners.

NREL INVESTMENT IN GEOTHERMAL RESEARCH AND CAPABILITIES



Preparing mixed-metal oxides at NRELs Field Test Laboratory Building. *Photo by Dennis Schroeder, NREL 38840*

POTENTIAL GEOTHERMAL AT NREL FLATIRONS CAMPUS FURTHERS INTEGRATED ENERGY SYSTEMS AT SCALE INITIATIVE

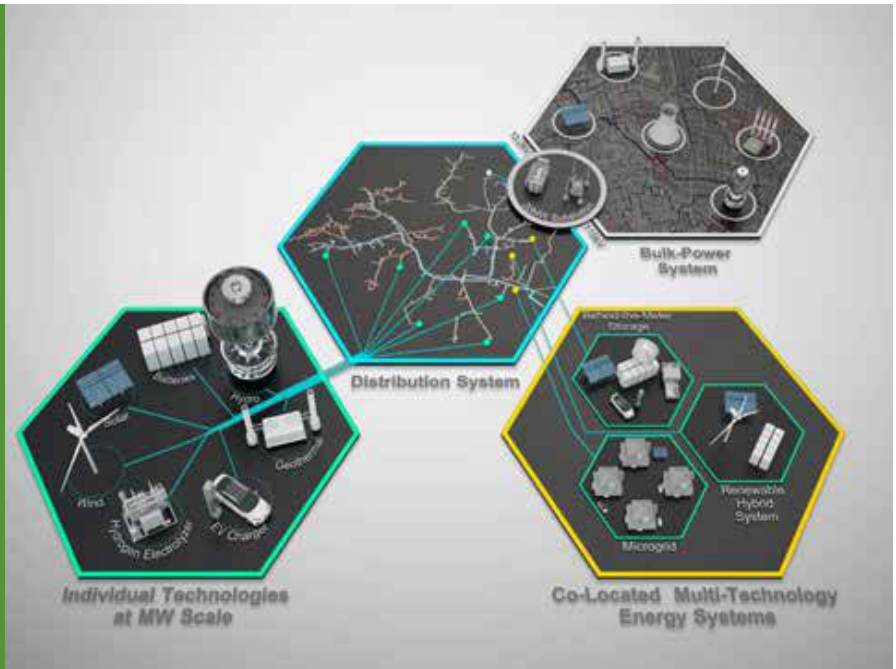
NREL invested planning and assessment funds to evaluate the potential to deploy geothermal technologies on the Flatirons Campus. The site offers a robust test bed for validation, optimization, and integration of renewable energy technologies, with intermittent renewable energy generation including wind turbines, photovoltaic panels, energy storage systems, and a controllable grid interface that provides immediate, validated performance information for campus equipment.

The opportunity assessment indicates that the diverse geology of the Flatirons Campus offers potential to further NREL Integrated Energy Systems at Scale (IESS) R&D objectives, reduce campus electricity and gas consumption, advance geothermal hardware and subsurface technologies, develop and validate energy storage concepts and technologies, and perform real-time, grid-scale testing of flexible geothermal technology integration with intermittent renewable sources.

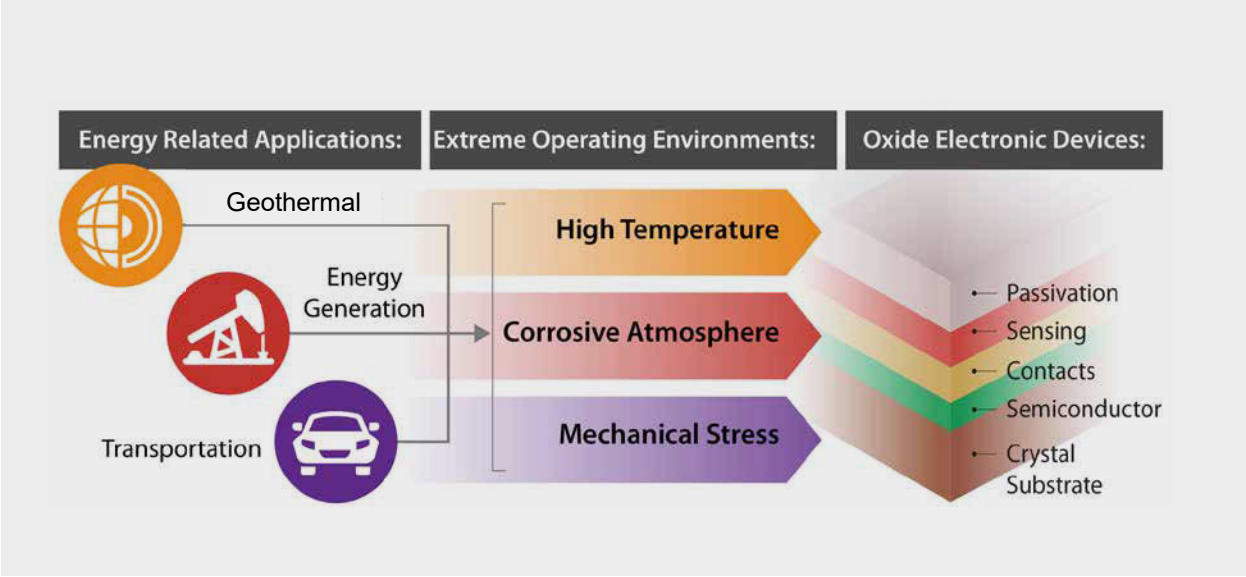
The available geothermal resource at the Flatirons Campus is not incredibly hot, nor does it have large volumes of fluid—making it an ideal testbed for demonstrating and evaluating Geothermal Anywhere technologies.

An opportunity for geothermal heat pump systems evaluation was identified at the Flatirons Campus as well as at NREL's South Table Mountain Campus, where several geothermal heat pumps are already installed. Expanded characterization of the performance of these existing heat pump systems can inform deployment of similar systems at Flatirons Campus and of heat pump systems nationwide.

Impacts: Identified new opportunities to support DOE research priorities, further NREL's IESS initiative, and demonstrate replicable Geothermal Anywhere technologies.



NRELs Integrated Energy Systems at Scale Initiative identifies four main capability areas including co-located, multitechnology energy systems such as those at the Flatirons Campus. *Image by Josh Bauer, NREL*



Energy-related applications of wide-bandgap oxide materials research extend beyond geothermal to energy generation and transportation. *Image by Al Hicks, NREL*

WIDE-BANDGAP OXIDE MATERIALS FOR HIGH-TEMPERATURE ELECTRONIC DEVICES

Improved high-temperature electronics are necessary to increase the efficiency of technologies including geothermal energy, advanced manufacturing, and electric vehicles. Currently, the performance and reliability of existing semiconductor devices are inadequate for many high-temperature electronics applications. A compelling way to address these challenges is to use wide-bandgap oxide semiconductors. NREL is investing in research in wide-bandgap oxide materials for high-temperature electronic devices, to develop Ga_2O_3 diodes that can operate in ambient temperatures of 500°C, and to demonstrate transistors based on new oxide semiconductors.

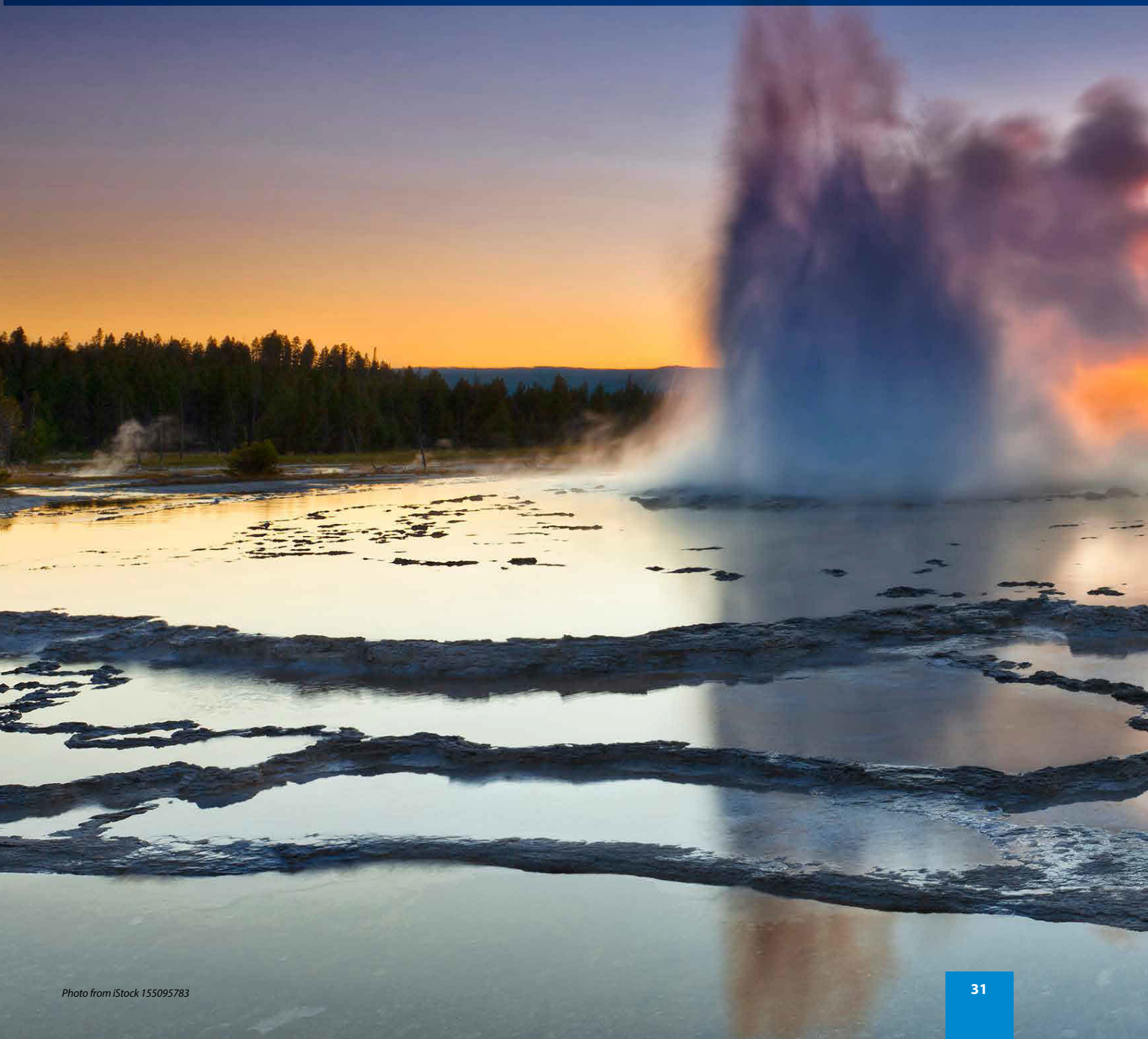
Ga_2O_3 diodes will be fabricated using molecular beam epitaxy and characterized for electrical performance at high temperatures. Device fabrication efforts will be guided by device simulations of their performance. Thermomechanical reliability modeling and techno-economic analysis will be performed to evaluate reliability and potential cost of the packaged Ga_2O_3 high-temperature electronics devices. For candidate ternary and binary oxide semiconductors identified as dopable, proof-of-concept transistors will be fabricated by laser epitaxy and characterized at room temperature.

The project leverages the major strengths of wide-bandgap oxide semiconductors for high-temperature environments, (wide bandgap, good oxidation resistance) and circumvents their well-known weaknesses (low thermal conductivity, poor doping at room temperature). The research will further establish NREL as a leader in the field of high-temperature electronics and will lead to additional exploration in this rapidly growing area of interest to both DOE and the Department of Defense.

In addition to the new analysis, NREL is a part of the Next Generation Power Electronics National Manufacturing Innovation Institute—also known as PowerAmerica—whose mission is to make wide bandgap semiconductors cost-competitive with their silicon-based counterparts.

Impacts: Increased efficiency of technologies related to geothermal drilling, advanced manufacturing, and electric vehicles; establishes NREL as a leader in the rapidly growing field of high-temperature electronics

PUBLICATIONS AND COMMUNICATIONS



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WEBSITE ANALYTICS

Metrics reflect user analytics for *NREL.gov/geothermal* between October 1, 2018 and September 30, 2019.

Users: **10,471**
Sessions: **12,215**
Pageviews: **20,483**
Bounce Rate: **71.3%**

Top Referrers:
1. **Direct** (46.1%)
2. **Google** (39.8%)
3. **Bing** (1.8%)
4. **T.co** (1.1%)
5. **All others** (11.2%)

Top States by Sessions:
1. **Colorado** (1,414)
2. **District of Columbia** (1,345)
3. **Virginia** (1,027)
4. **Maryland** (729)
5. **Kansas** (695)

Channels Driving Engagement:
1. Direct: **5,627** sessions
2. Organic Search: **5,283** sessions
3. Referral: **976** sessions
4. Social: **278** sessions
5. Email: **50** sessions

Average Session Duration: **00:01:18**
Average Time on Page: **00:01:54**
Pages per Session: **1.68**

New vs. Returning Users:
8,711 New Visitor Sessions
3,504 Returning Visitor Sessions

Users by Device Type
Desktop: **8,100**
Mobile: **3,094**
Tablet: **1,021**

Total visitors to the website increased **by 50%** as compared to the previous year, and pageviews **increased by 28%.**

NREL's geothermal website highlights current research, staff biographies, recent publications, data, tools, facilities, and partnering opportunities.

OUTREACH AND SOCIAL ACCEPTANCE

NREL.gov Features and News Releases

1. NREL Expands Research in Geothermal and Solar Desalination (Dec. 10, 2018) *https://www.nrel.gov/news/program/2018/nrel-expands-research-in-geothermal-and-solar-desalination.html*
2. NREL Experts Give Added Steam to Geothermal Industry (Aug. 13, 2019) *https://www.nrel.gov/news/program/2019/nrel-experts-give-added-steam-to-geothermal-industry.html*

SOCIAL MEDIA CONTENT, IMPRESSIONS, AND ENGAGEMENT

Content posted to @NREL_MechTherm, the Twitter feed of NREL's Mechanical and Thermal Engineering Sciences directorate, included 32 geothermal tweets, which generated:

- 99,270 impressions
- 965 engagements, including 272 likes, 178 retweets, and 153 clickthroughs.

CONFERENCES AND EVENTS

- AngloAmerican Open Forum
- GEORG Geothermal Workshop
- INNO-Drill Workshop
- Stanford Geothermal Workshop
- King Abdullah City for Atomic and Renewable Energy (K.A.CARE) Conference
- Geothermal Resources Council Annual Meeting
- Interagency Power Group Renewable Energy Conversion Working Group Meeting

PATENT APPLICATION

Use of underground depleted gas wells for compressed-gas energy storage, United States Patent & Trademark Office Application No. 16/515,923 filed July 18, 2019.

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8. McTigue, Joshua, Jose Castro, Greg Mungas, John King, Nick Kramer, Daniel Wendt, Kevin Kitz, Joshua Gunderson, Craig Turchi, Nick Kincaid, and Guangdong Zhu. 2019. "Techno-Economic Assessment of Geothermal Power Plants Hybridized with Solar Heat and Thermal Storage." Proceedings of the 44th Workshop on Geothermal Reservoir Engineering, 11-13 February 2019, Stanford, California. *https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2019/Mctigue.pdf*

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18. 18. Reese, Samantha, Timothy Remo, Johney Green, and Andriy Zakutayev. 2019. "How Much Will Gallium Oxide Power Electronics Cost?" *Joule*, April 2019. DOI: 10.1016/j.joule.2019.01.011

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