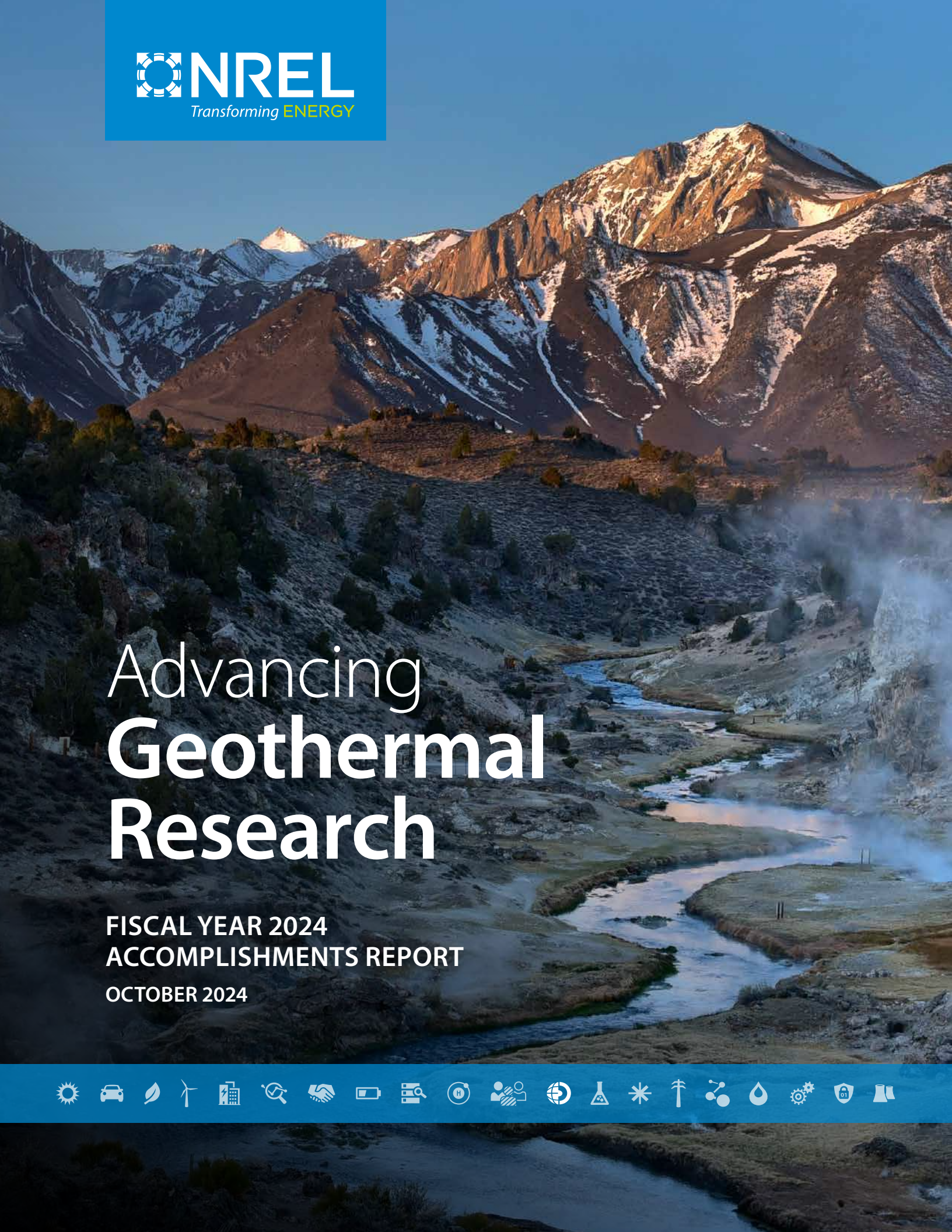
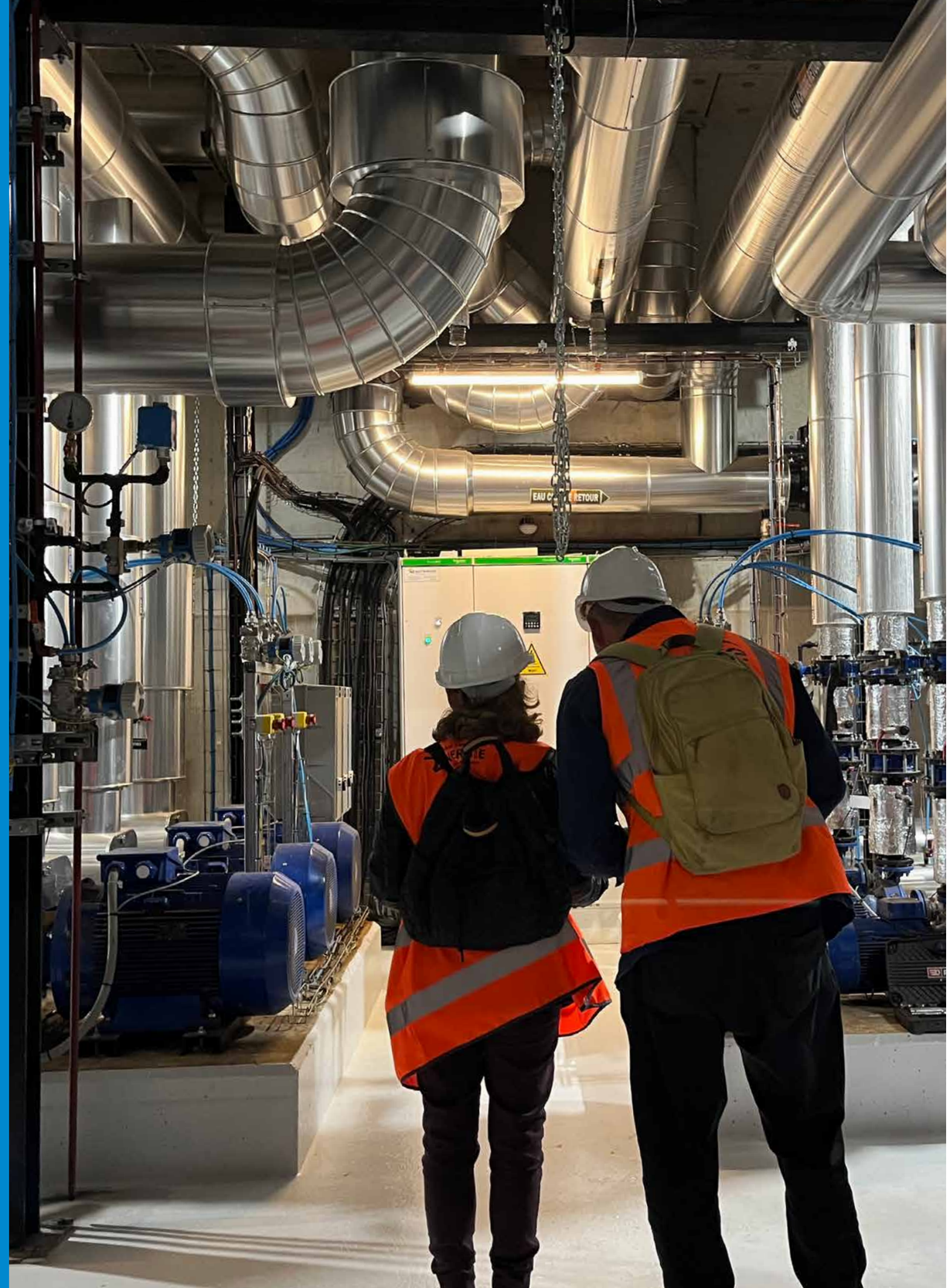


NREL
Transforming ENERGY

Advancing Geothermal Research

FISCAL YEAR 2024 ACCOMPLISHMENTS REPORT

OCTOBER 2024



EXECUTIVE SUMMARY

Geothermal resources have delivered renewable electricity for more than 100 years, and renewable heat for far longer, but recent research and advancements have shown that geothermal is more than a 24/7 clean energy source. With the ability to also provide cooling and storage—plus the potential to access critical minerals, capture and sequester carbon, produce green hydrogen, and more—geothermal technologies and resources are emerging as key solutions to the climate crisis.

In fiscal year 2024 (FY24), the National Renewable Energy Laboratory (NREL) broadened its research, development, demonstration, and deployment (RDD&D) portfolio and partnerships with exciting innovations such as next-generation geothermal technologies for power, geothermal energy networks for heating and cooling, subsurface thermal energy storage, well repurposing, and more.

In support of the U.S. Department of Energy (DOE) Geothermal Technologies Office's (GTO) mission to increase geothermal energy deployment through research, development, and demonstration of innovative technologies that enhance exploration and production, NREL led impactful research in geothermal technologies and resources, market acceleration, and grid integration while also demonstrating leadership in the sector and increasing stakeholder engagement and outreach efforts.

NREL's Intelligent Campus Program Manager Michelle Slovensky visits the networked geothermal heat pump system beneath the 2024 Olympic Village in Paris, France. *Photo by Amanda Kolker, NREL*

Front and back cover: Hot Creek Geothermal Site views, Eastern Sierras, California. The steam from the creek rises on a frosty morning, backdropped by the perfectly illuminated mountain range. *Photo from Getty Images 1462729207*

RESEARCH, DEVELOPMENT, DEMONSTRATION, AND DEPLOYMENT

The NREL geothermal program's vision is that geothermal technologies are key to the deep decarbonization of the nation's thermal and electrical energy systems by providing firm, renewable, and reliable 24/7 energy to grids, communities, and buildings. Geothermal energy boosts resilience by enhancing grid stability and energy security—with the smallest footprint of any renewable.

Through our work with GTO and other partners, NREL strives to support the strategic goals set forth by GTO in 2022: Drive toward a carbon-free electricity grid by supplying 60 gigawatts (GW) of enhanced geothermal systems (EGS) and hydrothermal resource deployment by 2050; decarbonize building heating and cooling loads by capturing the economic potential of 17,500 geothermal district heating installations and by installing geothermal heat pumps in 28 million households nationwide by 2050; and deliver economic, environmental, and social justice advancements through increased geothermal technology deployment.

In FY24, NREL continued growing the geothermal program through the expertise of its research team to further our mission to increase geothermal energy deployment and promote energy efficiency through strategic analysis, scientific research, development and demonstration of innovative technologies, and technology transfer through strategic partnerships. In FY24, NREL had 66 active agreements supported by GTO, and 11 agreements with strategic partners outside of GTO.

NREL's geothermal RDD&D efforts are centered around three pillars: technologies and resources, market acceleration, and grid integration. These research pillars support NREL's four strategic goals, as follows:

- **Strategic Goal 1:** Advance geothermal technology by research, development, and deployment of innovative technologies, such as EGS; closed-loop geothermal (CLG); geothermal heating and cooling; storage; mineral extraction; and well repurposing.
- **Strategic Goal 2:** Demonstrate the value of geothermal in a decarbonized energy sector by strategic analysis and modeling of the impact of geothermal power and heating/cooling technologies on current and future grids.
- **Strategic Goal 3:** Reduce geothermal development risk through research, development, and demonstration of new exploration, drilling, and subsurface characterization methods and leveraging artificial intelligence, machine learning, and play fairway analysis.
- **Strategic Goal 4:** Accelerate deployment by researching the geothermal market and exploring the economic, environmental, and social justice impacts of geothermal energy use.

LABORATORY INVESTMENT IN GEOTHERMAL RESEARCH CAPABILITIES

NREL made critical investments to further the uptake of geothermal technologies on NREL's campus in FY24. Researchers examined geothermal technology options for the planned South Table Mountain Energy Park, which will serve as a government and industry hub to translate research to market. Modeling was also conducted to explore replacing the current heating system at the NREL South Table Mountain Campus with geothermal heat pumps (GHP), including drilling test wells in summer 2024. Improvements were made to the Geothermal Showcase GHP System on NREL's Mesa Top Campus to allow for long-term performance monitoring and planned educational efforts.

STRATEGIC PARTNERSHIPS

NREL's work is highly collaborative, with much of our GTO-supported RDD&D activities occurring in partnership with other national laboratories, as well as universities, companies, state and federal agencies, and other entities. In FY24, NREL also had cooperative research agreements outside of DOE that supported a range of RDD&D efforts, including partnerships with utilities (e.g., Con Edison in New York City, CPS Energy in Texas, IDP Energy in North Dakota), the Department of Defense (U.S. Air Force and U.S. Army), the Port Authority of New York and New Jersey, the Bureau of Land Management, and more.

INDUSTRY LEADERSHIP

NREL continued to play a pivotal leadership role in advancing geothermal energy by hosting several industry workshops, briefing energy analysts on updated geothermal data and functionality in NREL tools, participating in high-profile initiatives such as hosting a delegation from Iceland, presenting key research at various geothermal conferences, and more.

EXPANDED STAKEHOLDER ENGAGEMENT AND OUTREACH

NREL researchers published 50 technical reports, conference papers, journal articles, presentations, posters and fact sheets, and expanded reach via **www.nrel.gov/geothermal**, industry conferences, and social media.

FY24 NATIONAL LABORATORY PARTNERS

- Lawrence Berkeley National Laboratory
- Idaho National Laboratory
- Oak Ridge National Laboratory
- Sandia National Laboratories
- Pacific Northwest National Laboratory
- Los Alamos National Laboratory

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RESEARCH, DEVELOPMENT, DEMONSTRATION, AND DEPLOYMENT

NREL GEOTHERMAL RESEARCH PROGRAM
OVERVIEW AND DEVELOPMENT HIGHLIGHTS

NREL's Geothermal Research Program has three pillars:

- Technologies and Resources
- Market Acceleration
- Geothermal Grid Integration.

TECHNOLOGIES AND RESOURCES RESEARCH PILLAR

NREL's expertise in subsurface modeling, geothermal exploration, resource assessment and characterization, site development, operations and optimization, techno-economic analysis, geospatial and geoscientific analysis, data science, and communications contributes to the advancement and commercial-scale deployment of geothermal technologies. These technologies include geothermal power generation, direct use, geothermal heat pumps, subsurface storage, and hybrid technologies. There are a broad range of commercial and emerging geothermal technologies being evaluated and considered by NREL's geothermal research program.

MARKET ACCELERATION RESEARCH PILLAR

Through data collection, market and policy analysis, and stakeholder engagement, NREL's market acceleration efforts further the role of geothermal energy in supporting a more efficient and effective U.S. electricity system. NREL's cross-cutting activities in market acceleration leverage our unique analytical capabilities to address nontechnical barriers to geothermal deployment, including policy and regulatory analysis, analyzing geothermal and component markets and supply chains, and conducting stakeholder engagement and outreach activities.

GEOTHERMAL GRID INTEGRATION RESEARCH PILLAR

NREL works with government and industry partners to optimize strategies for effectively interconnecting renewable generation with the electric power grid, and evaluating the grid impact of geothermal heating/cooling and storage deployment. As more variable renewable generation resources are added to the electric grid, NREL is demonstrating how geothermal can bring value by providing clean, firm power and heating/cooling, and added value in the areas of cybersecurity, flexible generation, storage, and other grid services.

Members of the DEEPEN project visit the Geysers Geothermal Field in California as part of a workshop on geophysical methods for detection and characterization of superhot geothermal resources. Pictured: Anne Obermann (ETZ Zurich), Whitney Trainor-Guitton (NREL), Craig Hartline (Calpine), Ásdís Benediktsdóttir (Reykjavik Energy), Hannah Pauling (NREL), Nicole Taverna (NREL), Vala Hjörleifsdóttir (University of Iceland), Nadege Langet (NORSAR), Bettina Goertz-Allman (NORSAR), and Amanda Kolker (NREL). *Photo by Janet Pike, NREL*

De-Risking Exploration for Geothermal Plays in Magmatic Environments

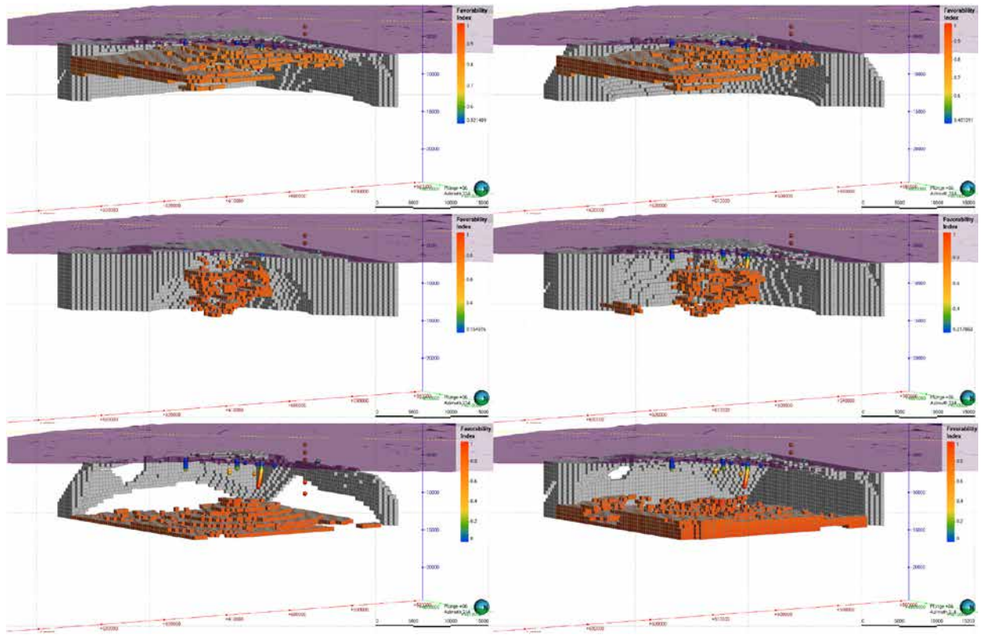
The DErisking Exploration for geothermal Plays in magmatic ENvironments (DEEPEN) project was a three-year, multinational research initiative to find ways of derisking exploration for supercritical/superhot geothermal resources through observation and modeling. International partners focused on the development and testing of new geophysical and geochemical tools for detection of superhot and supercritical resources in Iceland.

The U.S. team focused on the development of a derisking methodology for multiple geothermal targets in magmatic settings (conventional hydrothermal, superhot EGS, and supercritical "plays") through play fairway analysis (PFA) and modeling. The first step in this process involved the development of training sites. Exploration techniques and the resulting evidence layers of data and models from the training sites were ranked in terms of their ability to address key risk factors in high enthalpy plays. Quantitative weights were developed for each of the evidence layers based on expert opinions and a statistical learning-based approach. All datasets from the sites underwent quantitative data integration in 3D modeling software.

To the resulting set of 3D models, models of ore deposits formed in supercritical conditions were added and evaluated to define the key geologic elements for the "root zone" of magmatic geothermal systems, and to identify indicators for the presence of supercritical fluids. Findings from those models were input into thermo-mechanical-hydrologic-chemical models built by Lawrence Berkeley National Laboratory to characterize superhot geothermal reservoirs (>300°C). Key findings suggest a zone of permeability at the brittle-ductile transition zone related to induced hydrofracturing from magma emplacement and/or phase segregation, and that diverse pressure-temperature paths cause a wide spectrum of co-existing fluid types.

The DEEPEN PFA methodology was tested on Newberry Volcano in Oregon, which is a target for superhot EGS development. As part of the work, additional geophysical data were collected for zones where the magmatic plumbing system was modeled to reach shallower depths. The multi-physics dataset (MT, gravity, seismic) combined with joint inversion and other evidence layers was used to develop 3D favorability volumes for multiple plays in that system. Outcomes revealed a previously undetected potential conventional hydrothermal "blind" system; thus Newberry is potentially a multi-play geothermal field.

Superhot EGS component favorability models generated using expert weights (left) and statistical weights (right), for insulation (top), a fracturable EGS reservoir (middle), and heat source (bottom). Uncertainty mask (gray blocks) sliced to allow a view of the favorable area.
Graphic by Nicole Taverna, NREL



Panoramic view from Paulina Peak, Newberry National Volcanic Monument near Bend, Oregon.
Photo from Getty Images 1039332738

LEARN MORE

Taverna, N., Pauling, H., Trainor-Guitton, W., Kolker, A., Mibei, G., Dobson, P., Sonnenthal, E., Tu, X., and Schultz, A. "De-risking superhot EGS development through 3D play fairway analysis: Methodology development and application at Newberry Volcano, Oregon, USA." Geothermics, V. 118.

bit.ly/3YfuToW

PRINCIPAL INVESTIGATOR:
Amanda Kolker

IMPACT: Through a comprehensive analysis of exploration techniques, methods, and novel approaches to risk and uncertainty qualification, the DEEPEN project has advanced superhot geothermal resource characterization and therefore reduced development risk for superhot geothermal resources.

PARTNERS: Reykjavik Energy (Orkuveita Reykjavíkur, OR), Iceland GeoSurvey (ÍSOR), and the University of Iceland (UoI) in Iceland; the National Renewable Energy Laboratory (NREL) and the Lawrence Berkeley National Laboratory (LBNL) in the USA; EQUINOR and the Norwegian Seismic Array (NORSAR) in Norway, Das Deutsche GeoForschungsZentrum (GFZ) in Germany, Eidgenössische Technische Hochschule Zürich (ETHZ) in Switzerland, and IFP Energies Nouvelles (IFPEN) in France.

RESEARCH AND DEVELOPMENT HIGHLIGHTS: TECHNOLOGIES AND RESOURCES RESEARCH PILLAR

NREL Addresses High Cost of Drilling With GLADE Project

PRINCIPAL INVESTIGATOR:
Geoffrey Kiptoo Mibei

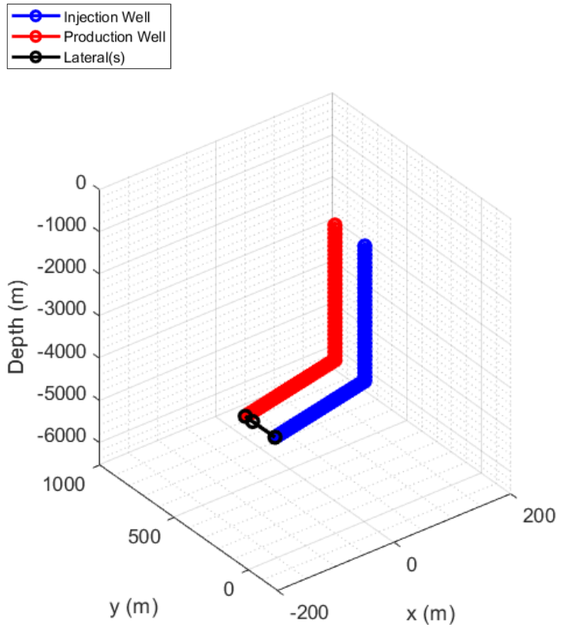
IMPACT: Reducing the drilling costs associated with geothermal development, leading to more widespread adoption of the drilling best practices and lower overall geothermal development costs.

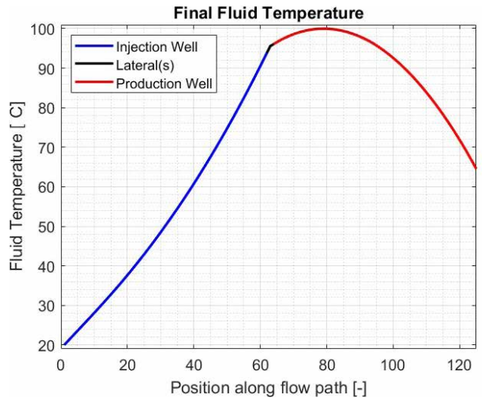
PARTNERS:
Occidental Petroleum, Los Alamos National Laboratory, Colorado School of Mines, Louisiana State University, Texas A&M, NOV, Particle Drilling Technologies, Intellicess, Drill Cool, Scientific Drilling, and Scout Downhole.

A new project is addressing one of the key barriers to geothermal adoption and development: the high cost of drilling geothermal wells. The Geothermal Limitless Approach to Drilling Efficiencies (GLADE) project will address these limitations by safely drilling two adjacent high-temperature geothermal wells with an increased daily drilling rate of penetration (ROP) by 25% or more. This will be achieved by evaluating several cutting-edge, high-temperature downhole tools and applying advanced cloud-based, real-time drilling optimization and non-productive time reduction technologies. The first of these wells is scheduled to be drilled in February 2025.

In FY24, NREL continued development of the wellbore heat transfer model using the laboratory's slender-body-theory tool, used for wellbore design and heat transfer simulations. NREL also led the subsurface characterization, preliminary insulated drill pipe model prior to drilling, and the techno-economic analysis of future geothermal power plant development on the site. This work provides useful insights in support of drilling speed comparisons within and between the twin wells, allowing for a more reliable evaluation of geothermal drilling equipment and practices.

Calculated temperature profile in an injection and production well. *Graphic by NREL*





Geometry of the preliminary twin well design in the SBT model. Circles represent grid points of the discretized wellbore profile. Each element length is 100 meters long, and the total number of elements is 126. Axes not drawn to scale. *Image by Geoffrey Kiptoo Mibei, NREL*

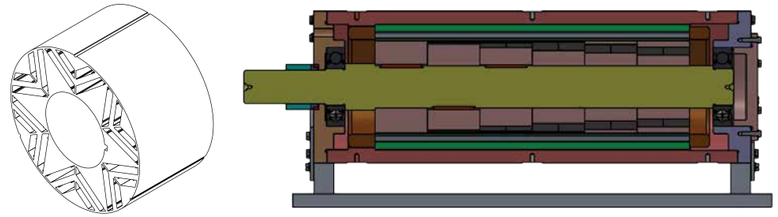
RESEARCH AND DEVELOPMENT HIGHLIGHTS: TECHNOLOGIES AND RESOURCES RESEARCH PILLAR

RePED 250 Revolutionizes Hard Rock Drilling in High Temperatures

PRINCIPAL INVESTIGATOR:
Devon Kesseli

IMPACT: Funded by ARPA-E, this project will lead to aster drilling in high-temperature geothermal environments, improving geothermal project economics, which should lead to increased deployment.

PARTNERS:
Tetra Corporation and TPL Inc.

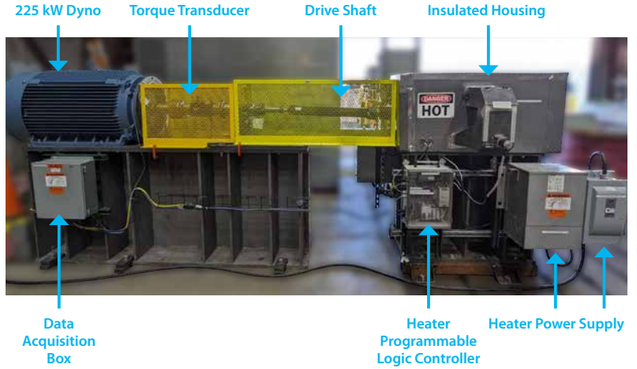


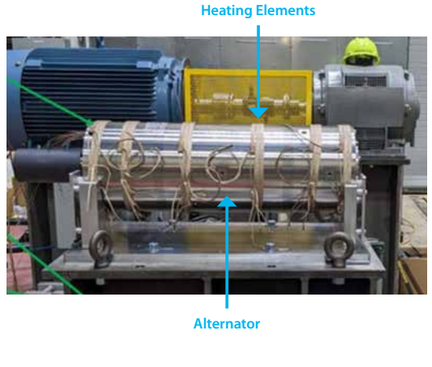
NREL's downhole high-temperature generator design. *Graphic by Devon Kesseli, NREL*

To transform the speed and lower the cost of hard rock geothermal drilling in 250°C environments, NREL partnered with TPL Inc. and Tetra Corporation to upgrade a repetitive, pulsed electric drill known as RePED. This updated RePED drilling system (RePED 250) is a high-power, high-temperature electronic drill designed to function within most elements of a conventional drilling system (e.g., drill pipe, steering tools, measurement-while-drilling systems, mud systems) without requiring specialized rigs or drill pipes.

NREL's primary role was developing a mud-turbine powered generator that can survive in downhole environments exceeding 250°C to generate the necessary power for drilling, as well as modeling how RePED deployment would affect the U.S. geothermal market. Project partners at Tetra Corporation and TPL successfully demonstrated the drill's effectiveness, cutting through a granite rock sample. In FY24, a prototype of NREL's patented generator design was delivered and tested on NREL's Flatirons Campus. The generator's performance was demonstrated at temperatures exceeding 250°C, meeting the modeled efficiency of 85% at temperature, far above the 60% initially targeted in the project milestone. The team is investigating additional applications for this device, in geothermal and other industries.

A novel high-temperature alternator at NREL's Flatirons Campus. The alternator is wrapped in heating elements and placed inside the insulated housing to measure performance at the extreme temperatures it will face in a geothermal well. *Graphic by Devon Kesseli and Dominique Barnes, NREL*





RESEARCH AND DEVELOPMENT HIGHLIGHTS: TECHNOLOGIES AND RESOURCES RESEARCH PILLAR

RIGS UP Gives New Life to Inactive Wells

The Repurposing Infrastructure for Gravity Storage using Underground Potential energy (RIGS UP) project aims to repurpose inactive (idle and orphaned) oil, gas, and geothermal wells for gravity-based energy storage.

The storage system, otherwise known as a gravity well (GrW), consists of a drivetrain that lowers a multiton weight within a vertical wellbore or the vertical section of a deviated/horizontal well. NREL is collaborating with a pioneer partner in this field, Renewell Energy, to design an optimal drivetrain—consisting of an electric motor, variable speed drive, winch drum, wire rope, and gearbox—that will result in minimal mechanical and thermal losses.

NREL is also supporting technology to market efforts that will accelerate commercial readiness of the GrW system. This includes the creation of a database of wells that currently are, or could be in the future, repurposed as GrWs.

In FY24, NREL's team finalized the optimized designs of five drivetrain candidates with 40 kWh of energy storage capacity and with round-trip efficiencies ranging between 75% and 85%. The design performances were derived from an electromechanical model developed by NREL that describes the charging and discharge operation of a GrW as a cylindrical weight that is lifted and lowered within a vertical wellbore at a constant speed. NREL also developed a well plug and abandon cost prediction model that will assist Renewell in identifying suitable inactive wells around the country that would give the best returns on investment.

A final major milestone in FY24 was the pilot demonstration of a GrW at an oil field in California, the first of its kind in the gravity storage industry. In FY25, the team will adopt operational and performance learnings from the first pilot into designing and deploying a second commercial pilot.

PRINCIPAL INVESTIGATOR:
Dayo Akindipe

IMPACT: Giving a second life to greenhouse gas emitting inactive wells via a gravity-based storage system with this project funded by ARPA-E.

PARTNERS:
Renewell Energy

LEARN MORE

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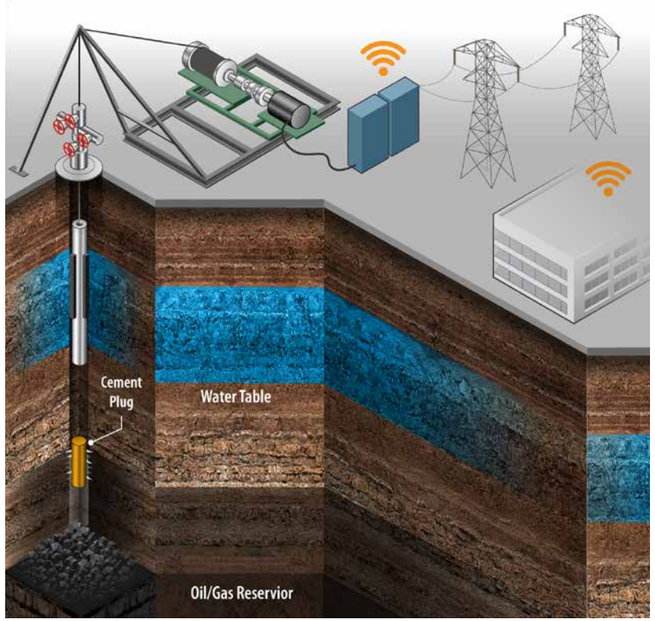

Illustration of the gravity well design showing the surface-mounted drivetrain, winch, and wire rope connected to the multiton weight in the well. *Graphic by Jessie Alexander, NREL*

RESEARCH AND DEVELOPMENT HIGHLIGHTS: TECHNOLOGIES AND RESOURCES RESEARCH PILLAR

Closed-Loop Geothermal Working Group Builds on Previous Work to Examine New Variations

Recently, there has been significant interest and investment in closed-loop geothermal companies and technologies. Closed-loop geothermal, also called advanced geothermal systems, is an emerging technology that does not require geographically limited hydrothermal resources to produce heat and/or power. As such, they fit into the suite of next-generation geothermal technologies, along with enhanced geothermal systems (EGS) and other emerging technologies for accessing geothermal energy "anywhere." The Closed-Loop Working Group (CLWG), led by NREL, continued investigating the techno-economic performance of different closed-loop geothermal designs in FY24.

Building off their work in previous fiscal years, where the CLWG looked at the performance of baseload operations in reservoirs where heat transfer is 100% conductive, the group focused on examining closed-loop system variations. This includes conductive cements and the impact of convection, which led to the development of two major publications describing findings.

The group also studied the impact of dynamic operation of a closed-loop system on its economic performance, working closely with partners on the simulation of flexible power plant operations accounting for hourly variations in ambient temperature, flow rates and electricity prices.

PRINCIPAL INVESTIGATOR:
Koenraad Beckers

IMPACT: Providing guidance on the effectiveness and cost of various closed-loop geothermal systems, allowing for more informed decision-making.

PARTNERS:
Sandia National Laboratories and Stanford University

LEARN MORE

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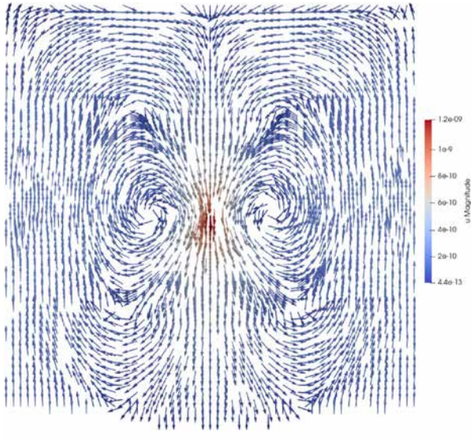
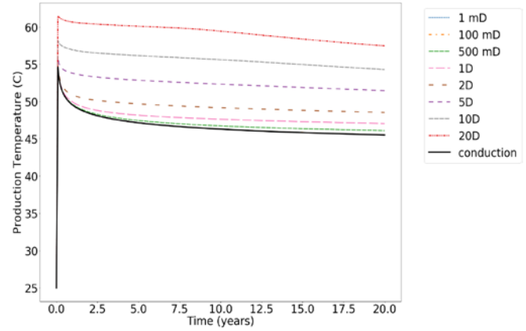


Cooled, denser formation water induces a downward flow near the closed-loop heat exchanger, giving rise to a pair of counter-rotating, buoyantly driven convection cells on either side of the tube. Heat exchanger (not shown) is in the center of the velocity field, into/out of the page. *Raquel Sara Pila Hakes Weston-Dawkes, Sandia National Laboratories*



Comparison of production temperatures for varying permeability at 1% rock porosity and a 30 C/km geothermal gradient. Results are shown for a working fluid with a mass flow rate of 10 kg/s. Permeability begins to have a clear impact at approximately 1 D. *Raquel Sara Pila Hakes Weston-Dawkes, Sandia National Laboratories*

RESEARCH AND DEVELOPMENT HIGHLIGHTS: TECHNOLOGIES AND RESOURCES RESEARCH PILLAR

Meeting Data Center Cooling Needs With Subsurface Thermal Energy Storage

With the exponential growth in data centers, management of the heat generated from processing, storing and communicating data has become a significant challenge. That is why NREL and a multi-lab team are evaluating the application of reservoir thermal energy storage (RTES) to thermal energy management for data centers. NREL analyzed the cooling potential and techno-economics of RTES for 70-MW, 30-MW, and 5-MW data centers in three different locations. The study calculated initial capital and lifetime operational costs for each system, and compared the levelized cost of cooling of the RTES-based to non-RTES-based center cooling systems. This innovative application of RTES to data centers can be broadened to other industrial cooling and waste heat applications in the future.

PRINCIPAL INVESTIGATOR:
Diana Acero-Allard

IMPACT: Reducing water consumption and energy needs for cooling data centers, as well as broadening energy storage solutions in a way that helps to meet decarbonization goals while also providing energy security and resilience.

PARTNERS:
Lawrence Berkeley National Laboratory and Idaho National Laboratory

Jennifer Granholm, U.S. Secretary of Energy, takes a tour of the High-Performance Computing Lab during a visit to NREL. NREL's data center was one of the cases analyzed as part of this FY24 project. *Photo by Werner Slocum, NREL*

RESEARCH AND DEVELOPMENT HIGHLIGHTS: TECHNOLOGIES AND RESOURCES RESEARCH PILLAR

Techno-Economic Analysis and Market Potential of Geological Thermal Energy Storage Charged with Solar Thermal and Heat Pumps for Long-Duration Energy Storage

Energy storage is increasingly necessary as Variable Renewable Energy (VRE) technologies replace fossil fuels for electricity generation and heating at a significant and increasing rate. Many energy storage solutions are being developed to address short discharge durations, but there is significant seasonal mismatch between VRE generation and electricity consumption. Technologies that can provide seasonal or long-duration energy storage (LDES) are therefore a critical need, which can shift energy generation from the summer to the winter, but these technologies must have utility-scale capacities and very low costs for market competitivity. Reservoir thermal energy storage (RTES), or geological thermal energy storage (GeoTES), is proposed as a low-cost solution for long-term energy storage as excess thermal energy can be efficiently stored in permeable reservoirs such as aquifers and depleted hydrocarbon reservoirs for several months.

This project investigated charging GeoTES with two different energy sources: (1) concentrating solar power (CSP) and (2) excess renewable electricity using heat pumps (henceforth known as a "Carnot Battery"). These systems expand deployment potential for geothermal technologies into new regions, which would open new markets. The stored thermal energy can be used to generate electricity and, uniquely, also directly produce heat that can be used by industrial processes. Furthermore, Carnot-Battery-GeoTES can also be used to form a cold storage reservoir (<5°C) in an aquifer, and this cold energy may also be used for building and industrial cooling.

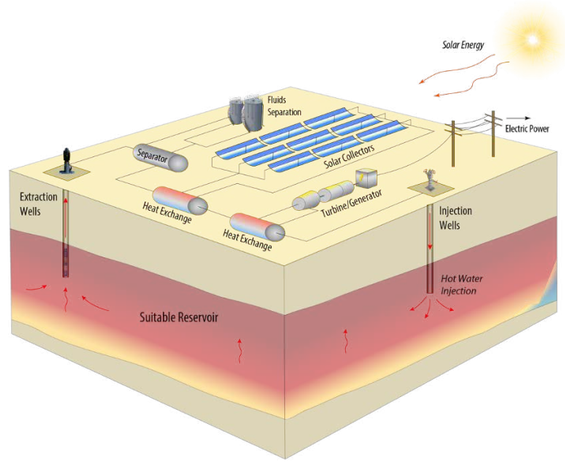
NREL developed techno-economic models to evaluate the commercial feasibility of GeoTES systems charged with these two energy sources, and compare to other storage technologies including competing LDES concepts. GeoTES models are based on technical performance inputs such as heat recovery efficiency, storage capacity per reservoir volume (i.e., power density), and round-trip efficiency, among other factors. Suitable reservoirs were initially identified in California and Texas. Case studies were conducted for locations in California and Texas, and comprehensive sensitivity analyses was also performed to evaluate these novel and impactful technologies. The results have attracted attention from multiple **media outlets** and will be published in peer-reviewed journals.

PRINCIPAL INVESTIGATOR:
Guangdong Zhu

IMPACT: Explore an emerging long-duration energy storage (LDES) concept to enable "geothermal anywhere" by evaluating technical feasibility and economic potential of GeoTES technologies hybridizing with solar thermal and Carnot Battery cycle.

PARTNERS: Idaho National Laboratory, Lawrence Berkeley National Laboratory, Premier Resource Management, and EarthBridge Energy

A rendering of the planned GeoTES system. *Graphic by Premier Resource Management*



RESEARCH AND DEVELOPMENT HIGHLIGHTS: TECHNOLOGIES AND RESOURCES RESEARCH PILLAR

De-Risking Next Generation Resilient Geothermal Hybrids With Exergetic

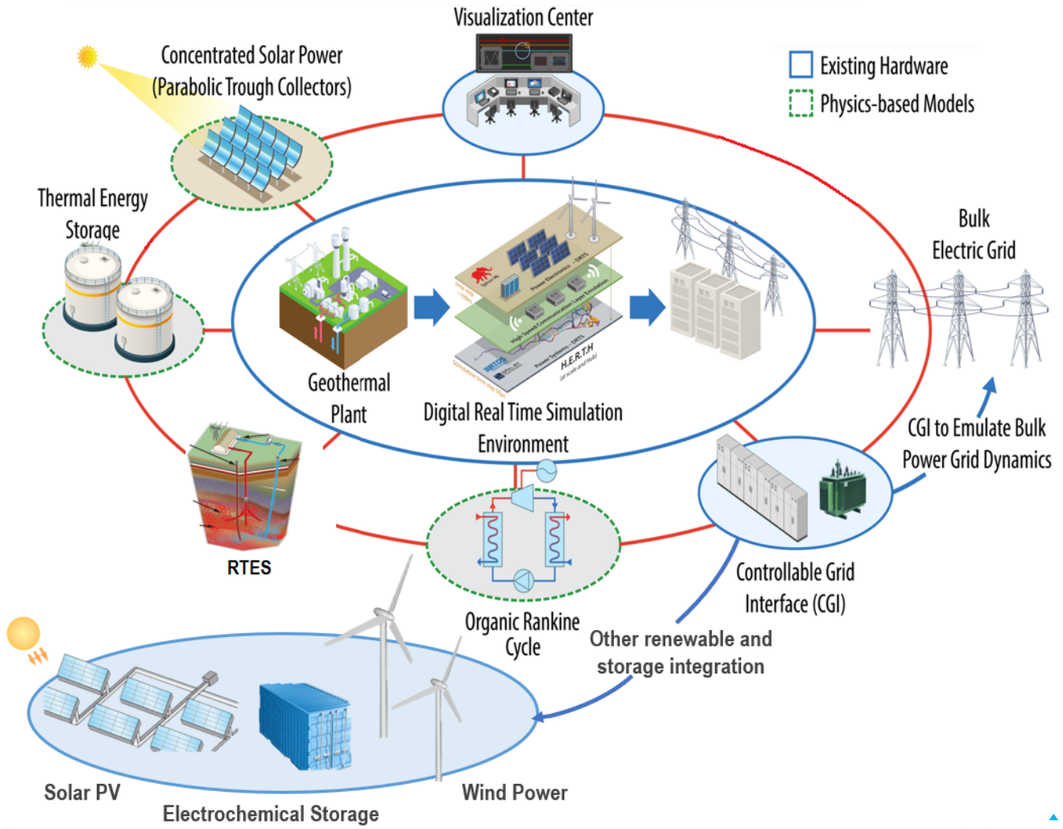
NREL researchers developed a geothermal-based hybrid real-time digital co-emulation environment based on existing physics-based models and assets through NREL's Advanced Research on Integrated Energy Systems (ARIES) platform. This system, Exergetic, can assess the technical and economic performance of geothermal hybrids and their capability to provide grid services to improve flexibility and resiliency.

This digital twin project demonstrates the technical, environmental, and economic value of geothermal hybrid energy systems with respect to a single geothermal plant. Developing a digital real-time co-emulation environment for geothermal hybrid systems is fundamental to assessing their behavior, interaction with other power generation and energy storage technologies, and the electric grid.

PRINCIPAL INVESTIGATOR:
Julian Osorio

IMPACT: Enabling the evaluation of technical risks associated with geothermal hybrid plants as well as their capability to provide grid services.

PARTNERS:
Clemson University and Florida State University



Multi-physics Digital Real Time Simulation Environment at NREL's Advanced Research on Integrated Energy Systems. *Graphic by NREL*

RESEARCH AND DEVELOPMENT HIGHLIGHTS: TECHNOLOGIES AND RESOURCES RESEARCH PILLAR

INGENIOUS Accelerates Discovery of Hidden Geothermal Systems

Geothermal research and development stands at a major crossroads. A critical amount of geological and geophysical data has been collected and geostatistical analyses have been done, but further work is required to addresses the wide-ranging scale of both the data and geologic heterogeneity that immensely influences the success of geothermal.

That is where INnovative Geothermal Exploration through Novel Investigations of Undiscovered Systems (INGENIOUS) comes in. The primary goal of INGENIOUS is to accelerate discoveries of new, commercially viable hidden geothermal systems, or those without surface evidence of a geothermal system, while reducing the exploration and development risks for all geothermal resources.

As part of a "developer's playbook" for discovering and characterizing hidden geothermal resources, NREL released an open-source value of information (VOI) tool. The VOI tool utilizes updated labeled datasets from the Great Basin integrated with knowledge gained from previous geothermal play fairway analysis (PFA) and machine learning projects to derisk exploration decisions. The VOI tool, along with preliminary data, will be workshopped with industry and other stakeholders at the 2024 Geothermal Rising Conference. The VOI app utilizes updated labeled datasets from the Great Basin and represents software tools to derisk geothermal exploration decisions.

PRINCIPAL INVESTIGATOR:
Whitney Trainor-Guitton

IMPACT: Providing geothermal developers with a tool to determine which data types are most useful when prospecting for geothermal wells, allowing for a more succinct process.

PARTNERS:
University of Nevada – Reno; United States Geological Survey; Utah Geological Survey; Idaho Geological Survey; Lawrence Berkeley National Laboratory; Raser Power Systems; Geothermal Resources Group; Hi-Q Geophysical; Aprovechar Lab L3C; Petrolern Ltd.; Innovate Geothermal Ltd.

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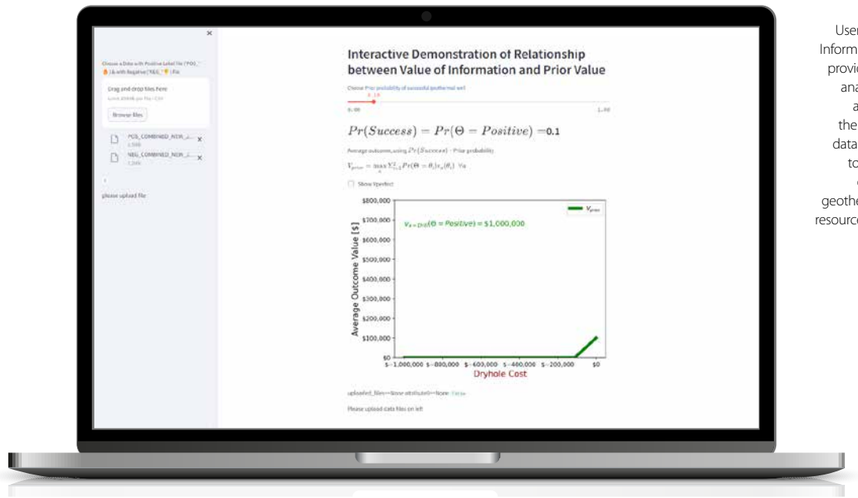
bit.ly/3YMPQI7



User interface for Value of Information software, which provides example decision analysis calculations and allows users to upload their labeled geothermal data to assess its reliability to distinguish between geothermal and non-geothermal (noneconomic) resources. *Graphic by Whitney Trainor-Guitton, NREL*

RESEARCH AND DEVELOPMENT HIGHLIGHTS: TECHNOLOGIES AND RESOURCES RESEARCH PILLAR

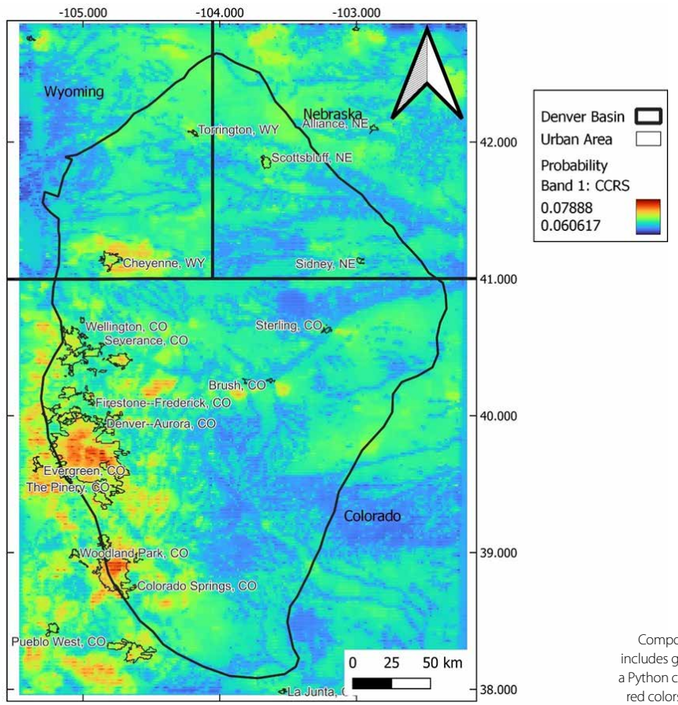
Analysis of Geospatial Datasets for Low-Temperature Geothermal Reveals Opportunities in U.S. Sedimentary Basins

PRINCIPAL INVESTIGATOR: Estefanny Davalos Elizondo

IMPACT: Accelerating the country's decarbonization efforts by identifying opportunities for utilizing low-temperature geothermal resources (< 150°C) in selected sedimentary basins with numerous population centers.

In FY24, NREL continued work to use geospatial datasets for mapping favorability of low-temperature geothermal resources with a focus on the Denver sedimentary basin. The project developed workflows, relevant datasets, and an extensible python toolset to create favorability maps for the focus area.

in FY24, NREL continued work on geospatial datasets for low-temperature geothermal resources with a focus on identifying favorable areas for development in the Denver sedimentary basin. The project developed workflows, relevant datasets, and a python code to create favorability maps for the focus area. Play Fairway Analysis methodologies developed in the first year of this effort were used as a reference and modified to identify favorable areas for development of low-temperature (<150 C) geothermal resources in the Denver basin by overlaying multiple datasets related to key criteria (geological, economic, and risk).; and choosing the best weighted criteria to identify suitable regions for GHC technologies (not including geothermal heat pumps) and other geothermal direct uses. The aim of the project is to use the newly developed, extensible, PFA code-base to replicate these methodologies in other sedimentary basins as a basis for low-temperature geothermal resources assessment on a broader scale.



Composite Criteria Favorability Map of the Denver Basin that includes geological, economic, and risk criteria, produced using a Python code 'geoPFA' and edited in QGIS. Higher probability in red colors and lower probability in blue colors. *Graphic by NREL*

Setting the Stage for the 2025 United States Geothermal Market Report

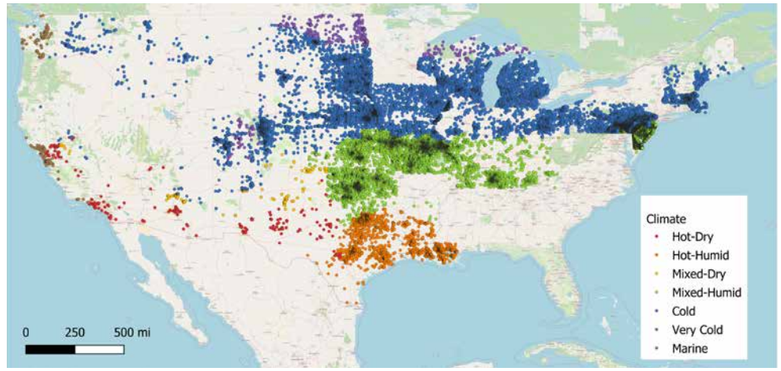
In FY24, NREL performed critical data collection and analysis to build the foundation for a future "United States Geothermal Market Report," expected to be published in 2025. The first time this market report has been updated since 2021, the 2025 edition will expand to new market sectors (e.g., in-depth analysis of the geothermal heat pump (GHP) market from single building to district heating and cooling applications) and include new analysis (e.g., the impact of market drivers, including incentives and regulatory policies at the state level, on the growth of the GHP market). Lastly, the accelerated progress of next-generation technologies since 2021, such as major advances in EGS and closed-loop geothermal, will be covered in the 2025 report.

The team compiled available data on over 8,000 GHP installations across the continental United States. Data entries include location, heat exchange method (open-loop and closed-loop), borehole configuration (vertical and horizontal), and capacity.

The team also assembled data on available incentives for GHPs in all U.S. states. These include utility-provided rebates and property tax exemptions to residential and commercial adopters of GHPs. An important update to an existing NREL database on geothermal direct use was initiated to ensure that the data represents up-to-date installed capacities for direct-use space and district heating applications. This new dataset covers use cases such as pools, resorts, greenhouses and other agricultural/industrial applications, which have not been updated since 2016.

Regarding the geothermal electricity market, the existing database on geothermal power purchase agreements (PPAs) was updated with PPAs signed after 2020. Revisions have been made to the installed capacities and planned capacity additions of geothermal plants across the country based on inputs from operators and developers and data compiled by the Energy Information Administration (EIA).

An assessment of the progress in other emerging technologies will also be included, such as superhot rock (SHR) geothermal, geothermal co-production in oil and gas wells, geothermal microgrids, flexible geothermal, reservoir and underground thermal energy storage (RTES and UTES), hybrid geothermal systems, and CO_2 plume geothermal. Other ancillary uses of geothermal wells for storage and geothermal brines as a source of lithium will also be reported.



Distribution of GHP installations across DOE's Building America climate zones. *Graphic by Hannah Pauling, NREL*

PRINCIPAL INVESTIGATOR: Dayo Akindipe

IMPACT: Data collection and analysis performed on the current state of the geothermal market and technologies will lead to the publication of NREL's 2025 United States Geothermal Market Report.

PARTNERS: Geothermal Rising

RESEARCH AND DEVELOPMENT HIGHLIGHTS: MARKET ACCELERATION RESEARCH PILLAR

Increasing Uniform Regulatory Certainty for Geothermal Project Development

PRINCIPAL INVESTIGATOR:
Aaron Levine and Frederick Randall III

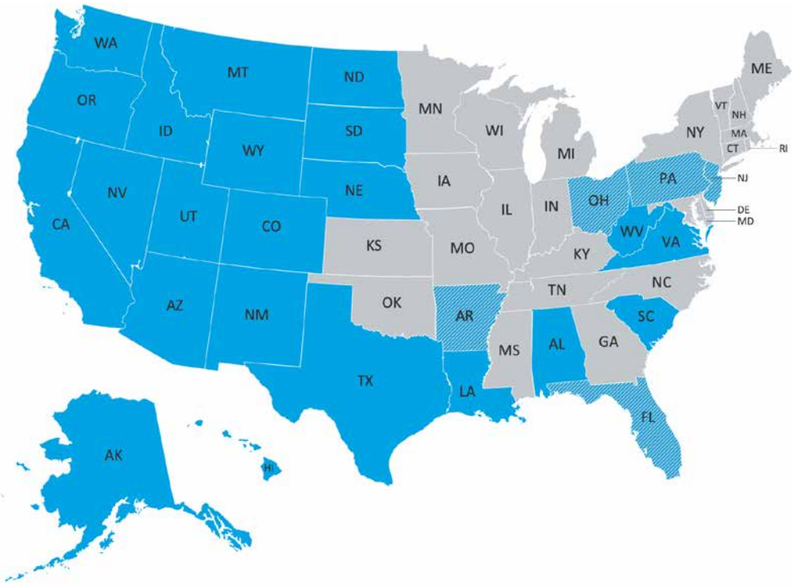
IMPACT: By creating accessible, consolidated resources on required authorizations and processes for existing geothermal regulations, as well as information for states that do not currently have geothermal regulations or are seeking to make updates to existing regulations to address changes in geothermal technology, this project mitigates a key aspect of uncertainty around geothermal energy development.

Regulatory and permitting authorizations are a key aspect of geothermal project development. Providing key geothermal stakeholders, such as developers and federal and state agencies, with up-to-date information on the geothermal regulatory processes is critical to reducing the impact of regulatory uncertainty on renewable energy development. In FY24, an NREL project team developed geothermal regulatory guidance documentation for utilization by states without existing geothermal regulations or states seeking to make updates to their current geothermal regulations.

This project included updating the **Geothermal RAPID Toolkit** for existing federal and state geothermal regulations, as well as authoring an NREL Technical Report titled *Topics and Considerations for Developing State Geothermal Regulations*. The NREL Technical Report is directed at informing policymakers on key geothermal issues in states that do not currently have geothermal regulations for electricity generation and/or direct use or are seeking to update their existing regulations to address changes in geothermal technology. The project team then conducted outreach and information dissemination activities to states with untapped geothermal resource potential.

State-Level Geothermal Regulations Across the United States

- Full Regulatory Program
- Definition of Geothermal Resources
- No Geothermal Regulations



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Map of state-level geothermal regulations across the United States identifying states that currently have regulations. *Graphic by Jessie Alexander, NREL*

RESEARCH AND DEVELOPMENT HIGHLIGHTS: MARKET ACCELERATION RESEARCH PILLAR

Geothermal Heat Pump Case Studies Raise Awareness

PRINCIPAL INVESTIGATOR:
Xiaofei Pu

IMPACT: Raising awareness about the benefits of geothermal systems in providing heating and cooling to a variety of climate conditions and building types, promoting large scale adoption.

To tackle the misconception that geothermal heat pumps are only suitable for specific and limited climate conditions, GTO funded the Geothermal Heat Pump Case Study project in FY24. The project featured 20 successful cases of geothermal heat pump applications across the United States to raise public awareness on the benefits of geothermal systems in providing heating and cooling to a variety of building types. Sites profiled included universities, public schools, residential communities, nature centers, corporate and government buildings, and even a bridge.

The final publication will be entitled "Geothermal Heat Pump Case Studies" and will include both print and web versions. An interactive map showing the sites and key details about each system is available on the EERE website.

Follow-on work in FY25 will include the amplification and refinement of the FY24 project as well as adding new case studies to this compilation.

Case study examples from the FY24 initiative to showcase geothermal heat pumps in action. *Graphic by NREL*

RESEARCH AND DEVELOPMENT HIGHLIGHTS: MARKET ACCELERATION RESEARCH PILLAR

FedGeo Program Makes Progress at Detroit Arsenal and West Point

PRINCIPAL INVESTIGATOR: Matt Mitchell

IMPACT: Supporting analysis to enable deployment of geothermal heating and cooling at federal locations will aid decarbonization efforts and promote adoption at additional sites.

PARTNERS: Oak Ridge National Laboratory, Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, Illinois State Geological Survey, Oklahoma State University, and the University of Wisconsin-Madison

In FY23, NREL entered into a multiyear partnership with other national laboratories, industry, and academia to support deployment of geothermal heating and cooling for the nation's largest energy user, the federal government.

The Federal Geothermal Partnerships (FedGeo) program is a joint effort between GTO and the Federal Energy Management Program (FEMP) to assist federal building owners with evaluating decarbonization through geothermal technologies.

The project, led by Oak Ridge National Laboratory with support from NREL, Lawrence Berkeley National Laboratory, and the Pacific Northwest National Laboratory, provides technical assistance on geothermal heating and cooling system implementation for federal buildings.

At each site, the team collected data, performed modeling of the buildings and subsurface, and performed thermal response tests; the team are developing a techno-economic feasibility report that will be accessible to not only the project stakeholders but also to the general public.

In FY24, NREL engaged with all the partners involved and worked to collect physical test data from two sites: the U.S. Army Garrison Detroit Arsenal in Michigan and the U.S. Military Academy at West Point. Drilling began at the Detroit Arsenal in May 2024, and at West Point in June 2024. Downhole geophysics logging, thermal response tests, and other work will complement well drilling at the two sites in FY24.

NREL will focus on collecting additional data to describe subsurface heat exchange potential, opportunities for building upgrades and retrofits to use geothermal heating and cooling technologies, and the financial viability of the designs. Those data will support detailed modeling and analysis efforts led by NREL for the two sites.

Well drilling for tests characterizing geo exchange resource potential at the West Point North Athletic Field Complex. *Photo courtesy of Bass Shakra, Energy Manager, DPW, West Point*

RESEARCH AND DEVELOPMENT HIGHLIGHTS: MARKET ACCELERATION RESEARCH PILLAR

Hawai'i State Outreach and Stakeholder Engagement

PRINCIPAL INVESTIGATOR: Faith M. Smith

IMPACT: Connecting with communities before any sort of renewable energy development is proposed is of critical importance to begin developing relationships and to learn from cultural and community wisdom. Listening sessions held in FY24 in Hawai'i illustrate a variety of opinions on geothermal power technologies with broad interest in geothermal cooling opportunities and a general interest in energy education.

PARTNERS: Thank you to the Community Council members!

- Piihonua Hawai'ian Homestead Community Association
- Hawaiian Electric
- Sustainable Energy Hawai'i
- Department of Hawaiian Home Lands
- University of Hawai'i
- Hawai'i State Energy Office
- Aha Moku Advisory Committee
- Hawai'i Green Growth
- Hawai'i Department of Land and Natural Resources
- Ulupono
- Hawai'i PUC
- Ormat
- Office of Hawaiian Affairs

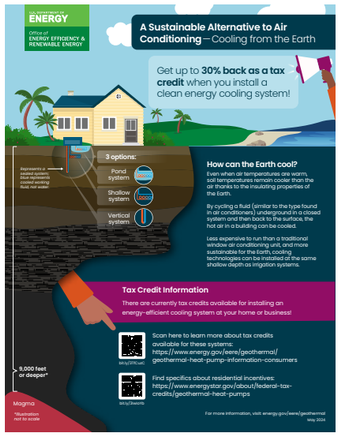
An NREL led, GTO funded effort focused on identifying and establishing relationships with stakeholders in Hawai'i hosted a series of listening sessions for energy stakeholders across the Hawaiian Islands to better understand perspectives on geothermal energy technologies, as well as encourage discussions about clean energy development more broadly in a state that generates as much as 80% of their electricity from petroleum.

This effort builds on previously funded efforts focused on the state of Alaska with a similar emphasis on working directly with stakeholders to understand their current and potential future relationship with geothermal, identify barriers to geothermal development from their perspectives, and to provide recommended solutions to overcome any identified barriers throughout the state. This concept of state-level outreach and stakeholder engagement has been a unique effort seeking to address common misconceptions and concerns surrounding all types of geothermal technologies through direct engagement with stakeholders, outreach efforts, and in the creation of educational materials.

The FY24 initiative focused on state outreach and stakeholder engagement in the state of Hawaii. As part of this effort, the project team traveled to the islands of O'ahu, Maui, and Hawai'i during three separate trips to host stakeholder listening sessions on renewable energy, with geothermal as a particular focus. This project complements a resurgent interest by the state of Hawai'i and the federal government in geothermal as a source of clean, firm, local energy that could help the state achieve its commitments of a 100% clean energy portfolio by 2045.

Stakeholders, including community members, were encouraged to share their perspectives on energy in Hawai'i with the goal of bringing those interested in energy together and connecting communities with informational resources. Following the listening sessions where participants perspectives were captured, an overview of geothermal energy technologies was presented. Community perspectives varied from those supportive of all renewable energy technologies to individuals with concerns or distaste with geothermal energy. Barriers identified included data gaps, funding resources, and cultural concerns including a deep respect for Madame Pele - the goddess of volcanoes and fire. For many Hawaiians, Pele is revered as the creator of the islands. At all sessions, the team provided fact sheets on geothermal energy and sustainable cooling with the use of geothermal heat pumps.

The Hawai'i efforts will conclude with a final technical report published in FY25 summarizing the Hawai'i engagement efforts, including key themes heard from participants in engagement sessions.



The infographic illustrated here is an example of the materials shared with stakeholders. *Graphic by Joelynn Schroeder, NREL*

RESEARCH AND DEVELOPMENT HIGHLIGHTS: MARKET ACCELERATION RESEARCH PILLAR

Geothermal Data Repository Celebrates 12th Anniversary With One Million Annual Downloads, Upgrades

The DOE Geothermal Data Repository (GDR) celebrated its 12th anniversary as an open data repository by exceeding one million data downloads during FY24. This milestone emphasized the continued relevance of the GDR to geothermal energy developers, heating and cooling stakeholders, researchers, and the public.

Developed by NREL, the GDR is home to more than 1,200 datasets totaling over 147 TB of data. In FY24, an NREL team updated the repository with new features designed to improve user experience. This included a new AI research assistant called "AskGDR," a Large Language Model (LLM) instructed to improve the discoverability of geothermal data by helping guide users to datasets beyond simple keyword searches. AskGDR enables users to find data based on properties of the data, discover information contained within supporting documents, and explore data from projects related to their research objectives. Users can ask questions about the methods and assumptions included in the generation of included data and get answers instantaneously, without having to comb through hundreds of associated research papers.

PRINCIPAL INVESTIGATOR: Jon Weers

IMPACT: Protecting DOE's investment in research and development by providing persistent, universal access to the results of GTO-funded activities.

PARTNERS: The GDR works with all GTO awardees to help make their data universally accessible, and to date has assisted over 120 different organizations in managing their data.

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TOP 5 DOWNLOADS

#1 PoroTomo Natural Laboratory Horizontal and Vertical Distributed Acoustic Sensing (DAS)

#2 Brady's Geothermal Field - March 2016 Vibroseis SEG-Y Files and UTM Locations

#3 Brady's Geothermal Field Nodal Seismometer Data

#4 Evaluation Data of a High Temperature COTS (Commercial Off-the-Shelf) Flash Memory Module (TI SM28VLT32)

#5 Brady's Geothermal Field DASH Resampled in Time

The Geothermal Data Repository more than doubled total downloads in FY24. *Graphic by Joelynn Schroeder and Dominique Barnes, NREL*

RESEARCH AND DEVELOPMENT HIGHLIGHTS: MARKET ACCELERATION RESEARCH PILLAR

Community Geothermal Heating and Cooling Coalition Projects

More geothermal heating and cooling could be coming to a community near you, thanks to a new initiative funded by the U.S. Department of Energy (DOE) **Geothermal Technologies Office** (GTO). This initiative will provide up to **$13 million across two phases to support community-led coalitions** to evaluate district or networked geothermal technologies **for their area or application**.

NREL is a named coalition member supporting 4 of the 11 communities selected for community-scale geothermal heating and cooling design and deployment projects. Those coalitions include communities in Colorado (Carbondale), Vermont (Middlebury), and Alaska (Seward and a remote community near Nome). NREL is also supporting 2 of the 11 selected communities through other DOE programs (Communities-to-Clean Energy—C2C and Communities Leap—C-LEAP) by providing technical assistance on geothermal heating and cooling technologies to those communities.

All six projects are focused on developing, designing, and installing new or retrofitted geothermal district heating and cooling systems that supply at least 25% of the heating and cooling load in these communities. The systems tap into the earth's subsurface to provide low-carbon heating and cooling to both businesses and residential spaces via an underground distribution network that uses a variety of technologies, such as district-scale geothermal heat pumps and direct-use geothermal (i.e., hot water).

Learn more about the progress made in each community NREL is a coalition member of in the following sections.

Community Geothermal Heating and Cooling Design and Deployment Project Locations

NREL is a partner and funding recipient on 4 out of 11 GTO-selected community geothermal projects and provides technical assistance to two of the selected communities under other DOE programs. *Graphic by Nicole Leon-Molina, NREL*

RESEARCH AND DEVELOPMENT HIGHLIGHTS: MARKET ACCELERATION RESEARCH PILLAR

Community Geothermal Heating and Cooling Coalition Projects

COALITION FOR COMMUNITY-SUPPORTED AFFORDABLE GEOTHERMAL ENERGY SYSTEMS ENERGY (C2SAGES)

The C2SAGES project aims to connect engineering and design partners with the local gas utility to design and deploy a community scale, district heating and cooling system serving low- to medium-income households in Vermont. The geothermal system is designed to meet 100% of the heating and cooling loads of the residents and community. To support the coalition, the NREL team used building models to design the ground heat exchangers and underground piping network. The team has also provided other general design guidance and support to the coalition regarding aspects related to community geothermal systems.

PRINCIPAL INVESTIGATOR: Matt Mitchell and Saqib Javed

IMPACT: Supporting the design and deployment of a network connected, geothermal community heating and cooling system serving low- to medium-income households in Vermont.

PARTNERS: GTI Energy, Vermont Gas, LN Consulting, Frontier Energy

CARBONDALE COMMUNITY GEOTHERMAL COALITION—REPLICABLE MODELS FOR DECARBONIZING MIXED-USE RURAL COMMUNITIES

PRINCIPAL INVESTIGATOR: Xin Jin

IMPACT: Reducing greenhouse gas emissions through less dependence on natural gas and providing a case study of a replicable model for a small-scale zero energy district enabled by a geothermal loop system.

PARTNERS: Clean Energy Economy for the Region (CLEER) and the GreyEdge Group

The Carbondale Community Geothermal Coalition was formed to design, develop, and deploy an advanced fifth-generation geothermal energy system to enable a zero energy district, the Three Two Zero Energy District (32ZED) in downtown Carbondale, Colorado. The buildings within the 32ZED are currently reliant on natural gas combustion for heating, which results in high costs, significant greenhouse gas emissions, and poor air quality—both indoor and outdoor. The 32ZED aims to reach net zero energy for its members through partnerships, renewable energy generation and storage, a geothermal loop system for efficient heating and cooling, a just transition for local workforce in the oil and gas industry, and an innovative financial structure for rapid deployment by 2030.

NREL's role in this project is to lead the building and district system modeling, as well as support the design of the geothermal district loop, geothermal site assessment, and workforce development. In FY24, NREL's team developed building models to generate annual heating and cooling loads to inform the design of the ambient temperature district loop. NREL performed simulation validation to verify the designed geothermal energy system can meet 100% of the heating and cooling loads of the 32ZED under various scenarios.

The Carbondale Community Geothermal Coalition is focused on enabling a zero energy district in Carbondale, Colorado. *Photo from Aaron Orelup, GreyEdge Group*

RESEARCH AND DEVELOPMENT HIGHLIGHTS: MARKET ACCELERATION RESEARCH PILLAR

Community Geothermal Heating and Cooling Coalition Projects

PILGRIM HOT SPRINGS DIRECT-USE GEOTHERMAL DISTRICT HEATING AND COOLING

A new direct-use geothermal district heating and cooling (GDHC) system designed by NREL is providing space conditioning for tribal buildings in Pilgrim Hot Springs, Alaska. Utilizing innovative direct-use GDHC technologies, NREL and coalition members developed a scalable design that provides space heating and domestic hot water to buildings and cooling to food storage areas while promoting sustainability and reducing reliance on fossil fuels. The project's lead organization is Kawerak, a nonprofit organization that is part of the Unaatuq LLC consortium.

The project will provide plans for a system that provides 95% of space heating and domestic hot water needs with direct use and 80% of cooling needs.. The project will support the region's vision of reestablishing permanent tribal management and development of the traditional site, facilitating the creation of a spiritual retreat and training center, food production facility, and tourist destination.

PRINCIPAL INVESTIGATOR: Georgina Davis

IMPACT: Establishing renewable-based power, heating, and cooling for existing facilities will support the region's vision of revitalizing the area, bolstering both community resources and economic growth.

PARTNERS: Unaatuq LLC and DeerStone Consulting

CITY OF SEWARD HEAT LOOP PROJECT

PRINCIPAL INVESTIGATOR: Matt Mitchell, Saqib Javed, Robbin Garber-Slaght

IMPACT: Supporting design and deployment of unique, CO_2-based heat pumps of GHP system, which is improving the wellness of the Seward, Alaska, community.

PARTNERS: City of Seward, YourCleanEnergy LLC, AVTEC

The Seward Heat Loop Project aims to provide the City of Seward, Alaska, with over 90% of the space and domestic water heating to four existing city buildings currently using fuel-oil fired boilers: the library, Fire Hall, City Hall, and Annex. The proposed hot water district heating system will supply heat to the buildings, with thermal energy sourced from nearby Resurrection Bay and a heating plant operated by a series of rack-mounted CO_2 heat pumps located in the library basement.

NREL worked with the design team to evaluate the proposed heating system design. To do this, the team performed blower door tests and then developed and calibrated building energy models for the buildings.

The team then developed a dynamic model of the heating plant and distribution system. In addition, during the winter heating season and continuing through November 2024, the NREL team also deployed and collected data from temperature sensors located in a nearby test well to measure how the naturally warm water from Resurrection Bay affects the water column in the shoreline, where any future geothermal wells will be deployed.

The city of Seward, Alaska, is the location of a new district heat loop project that will provide over 90% of heating and cooling needs for select district buildings by utilizing heat pumps in the basement of the Seward Community Library and Museum. *Photo by Matt Mitchell, NREL*

Advancing Geothermal Research | 2024 Accomplishments Report

RESEARCH AND DEVELOPMENT HIGHLIGHTS: MARKET ACCELERATION RESEARCH PILLAR

Prizes and Collegiate Competitions

PRINCIPAL INVESTIGATOR:
Diana Acero-Allard

IMPACT: The 2024 Geothermal Collegiate Competition was also launched by NREL and DOE in FY24, with applications opening in August and the competition running during the fall academic semester to continue workforce development for the geothermal industry.

PARTNERS:
Seequent

NREL administers several GTO geothermal competitions and prizes, providing comprehensive strategic and logistical support, as well as outreach and program promotion.

GEOTHERMAL COLLEGIATE COMPETITION

The U.S. Department of Energy American-Made **Geothermal Collegiate Competition** is an annual challenge that offers college students experience in the renewable energy industry and the chance to win cash prizes for developing real-world geothermal solutions.

In FY24, 33 teams registered for the competition across two tracks (policy and technical). This was the highest number of participants the competition has seen in recent years and was due to thoughtful recruitment by the NREL competition administration team. NREL also put effort into connecting with Spanish speaking students, resulting in a **segment on Telemundo** with NREL's Diana Acero-Allard.

NREL geothermal researcher Diana Acero-Allard talks about the Geothermal Collegiate Competition with Telemundo. *Photo from Telemundo*

Winning teams in each track held geothermal stakeholder engagement events in **Oklahoma** and **Alaska** to showcase their projects and to underscore the importance of engaging with the local community. NREL supported the execution of these events and traveled to Elim, Alaska, and Norman, Oklahoma, to meet with the teams, partners, and communities.

The winning team in the Policy Track of the 2023 Geothermal Collegiate Competition visited their partner community of Elim, Alaska, to discuss geothermal technologies. *Photo by Joe Del Nero, NREL*

RESEARCH AND DEVELOPMENT HIGHLIGHTS: MARKET ACCELERATION RESEARCH PILLAR

Prizes and Collegiate Competitions

PRINCIPAL INVESTIGATOR:
Lisa Trope and Rachel Buck

AMERICAN-MADE GEOTHERMAL GEOPHONE PRIZE

The Geothermal Geophone Prize is designed to catalyze the development of high temperature, downhole capable, seismic monitoring tools for enhanced geothermal systems (EGS) in the American instrumentation community through a series of prize competitions with a total of $3.65 million in incentives.

As part of prize administration, NREL provides subject matter expertise as well as executing informational webinars, communicates with competing teams, promotes the prize to potential competitors, administers payments, and manages the external review process.

In 2024, the Geothermal Geophone Prize awarded five finalist teams $250,000 in cash prizes and $100,000 in vouchers to use with an industry expert or national laboratory to advance their seismometer prototypes. The prize will accept final built submissions in August 2025 and will award a grand prize winner in October 2025.

Five Geophone Prize finalist teams were chosen from across the country to receive $250,000 in cash prizes and $100,000 in vouchers to use with an industry expert or national laboratory to advance their seismometer prototypes. *Graphic by John Frenzl, NREL*

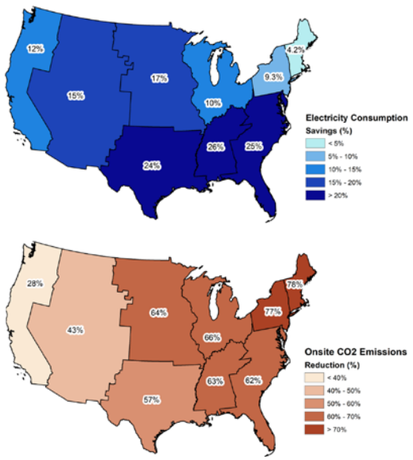
New Analysis Highlights Geothermal Heat Pumps as Key Opportunity in Switch to Clean Energy

This year, NREL and Oak Ridge National Laboratory (ORNL) completed a first-of-its-kind study—**Grid Cost and Total Emissions Reductions Through Mass Deployment of Geothermal Heat Pumps for Building Heating and Cooling Electrification in the United States**—to evaluate how mass deployment of geothermal heat pump (GHP) technology could impact grid costs and emissions.

NREL researchers partnered with ORNL to simulate the energy use impacts of retrofitting existing commercial and residential buildings with GHP systems in 14 climate zones across the contiguous United States. Six scenarios were modeled, using large-scale building energy simulation to assess the impacts of mass GHP retrofits on electricity usage and on-site carbon emissions in the buildings sector. The scenarios ranged from a base scenario with no GHP adoption to full GHP implementation and grid decarbonization scenarios.

Based on the modeling scenarios, the overall **value of widespread GHP adoption for decarbonizing the grid was found to be dramatic**. Widespread deployment of GHPs was found to potentially lead to lower peak demand, reduced infrastructure requirements, reduced emissions, and improved grid efficiency. The analysis also showed significant cost and carbon savings for consumers and the U.S. energy economy.

The analysis found that retrofitting 70% of all existing building stock in the contiguous United States with GHP systems could save as much as 593 terawatt-hours of electricity generation annually and avoid seven gigatons of carbon-equivalent emissions by 2050. This is equivalent to saving approximately 15% of the current U.S. annual electricity demand. Widespread geothermal heat pump installations could also save 24,500 miles of new grid transmission lines from needing to be built (36.7 TW-mi)—the equivalent of crossing the United States eight times—because of a reduced need for generation capacity, storage, and transmission compared to other energy pathways.



Geospatial representation of the percentage changes in annual electricity consumption (left) and carbon emissions from on-site combustion (right) resulting from the mass deployment of geothermal heat pumps paired with building envelope improvements in single-family homes. *Graphic by NREL and Oak Ridge National Laboratory*

The analysis also included preliminary results that suggest switching to geothermal heat pumps could reduce the challenges of maintaining electricity supply during high-use periods. And combining geothermal heat pumps with additional efficiency measures, such as building weatherization, can further increase benefits for energy users and the electricity grid while bolstering a domestic industry. This study was an impact analysis only and did not examine the costs of installing GHPs in building retrofits or new construction. Further analysis is planned to develop installation costs and compare those costs to the adoption scenarios presented in this study.

PRINCIPAL INVESTIGATOR: Jonathan Ho

IMPACT: Adopting widespread deployment of GHPs could have dramatic energy and cost savings and would help electrify the entire grid quickly and with less investment needed.

PARTNERS: Oak Ridge National Laboratory

NREL Modeling and Analysis Supports U.S. DOE "Pathways to Commercial Liftoff: Next Generation Geothermal Power" Report

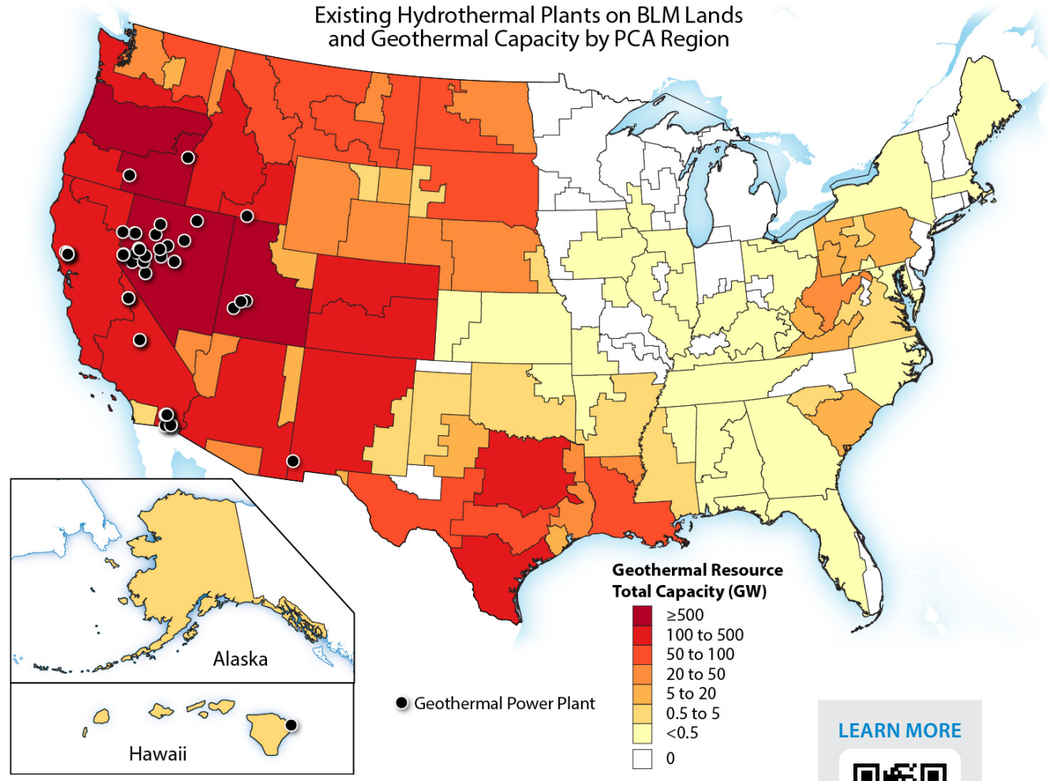
NREL partnered with multiple DOE offices in FY24 including GTO, the Office of Clean Energy Demonstrations (OCED), and others to conduct an analysis to support the DOE **"Pathways to Commercial Liftoff: Next-Generation Geothermal Power"** report. The team provided DOE with next-generation geothermal power data and scenario-based modeling for the report using the **Regional Energy Deployment System** (ReEDS), NREL's flagship capacity planning model for the power sector. Princeton University was also engaged to perform additional modeling and analysis using NREL data. In addition to modeling work, NREL researchers aided in the interpretation of capacity expansion and other results.

PRINCIPAL INVESTIGATOR: Jonathan Ho and Dayo Akindipe

IMPACT: NREL modeling and analysis helped inform OCED's pathway to next-generation geothermal power commercial liftoff report.

PARTNERS: GTO, OCED, Princeton University

FUNDING SOURCE: GTO



Total next-generation potential across the United States (red shading), overlain by locations of current conventional geothermal plants producing a total of 3.7 GW of power (black dots). *Graphic by NREL*

LEARN MORE

bit.ly/4fbxnL9

RESEARCH AND DEVELOPMENT HIGHLIGHTS: GRID INTEGRATION RESEARCH PILLAR

FLXenabler Examines Geothermal Flexibility to Decarbonize Integrated Energy Systems

PRINCIPAL INVESTIGATOR: Whitney Trainor-Guitton

IMPACT: Evaluating how geothermal heating, cooling and seasonal energy storage can reduce stress on the electric grid, provide flexibility, and enable uptake of decarbonized energy sources.

PARTNERS: SINTEF (Norway), Technical University of Vienna, and USGS

FLXenabler (Flexible Heating and Cooling and Geothermal Energy Storage as an Enabler for Decarbonized Integrated Energy Systems), a transnational collaborative project through Geothermica, seeks to evaluate and quantify the impact of the flexibility that geothermal heating, cooling, and storage can bring to decarbonized integrated energy systems.

In FY24, this project investigated geothermal heating and cooling technology integration with other renewable energy sources and thermal energy storage, as well as impacts on sector coupling and international decarbonization goals.

NREL grid modeling identified which U.S. states could benefit the most - in terms of fuel costs, CO_2 emissions, and grid savings - from grid flexibility provided by geothermal heating, cooling, and storage technology deployment. These technologies include geothermal heat pumps (GHPs) and subsurface thermal energy storage (or geologic thermal energy storage; GeoTES). (Table 1). These locations are the current focus of local modeling efforts that will incorporate physics-based performance modeling of these GHC technologies.

NREL applied NREL techno-economic codes to the results of subsurface flow and heat simulation results for representative cities in the states represented in Table 1 to identify where geoTES and GHP performance make it most economically practical.

Rank	State	Grid Costs [$/Unit]	Most Populous Metro Area		Second Most Populous Metro Area	
			Name	BA Climate Zone	Name	BA Climate Zone
1	NH	19,701	Manchester	Cold	Nashua	Cold
2	VT	20,107	Burlington	Cold	South Burlington	Cold
3	ME	20,293	Portland	Cold	Bangor	Cold
4	CT	14,153	Bridgeport	Cold	Hartford	Cold
5	MA	14,062	Boston	Cold	Worcester	Cold
6	RI	13,521	Providence	Cold	Warwick	Cold
7	MD	6,018	Baltimore	Mixed-Humid	Washington, D.C.	Mixed-Humid
8	OK	4,094	Oklahoma City	Mixed-Humid	Tulsa	Mixed-Humid
9	AZ	657	Phoenix	Hot-Dry	Tucson	Hot-Dry
10	NY	10,265	New York City	Cold	Buffalo	Cold

Table 1: Ten Most Favorable States for Addressing Heating and Cooling Using GHC With Storage. *Graphic by Jonathan Ho and Dominique Barnes, NREL*

RESEARCH AND DEVELOPMENT HIGHLIGHTS: GRID INTEGRATION RESEARCH PILLAR

Geothermal Analysis Portfolio

PRINCIPAL INVESTIGATOR: Whitney Trainor-Guitton

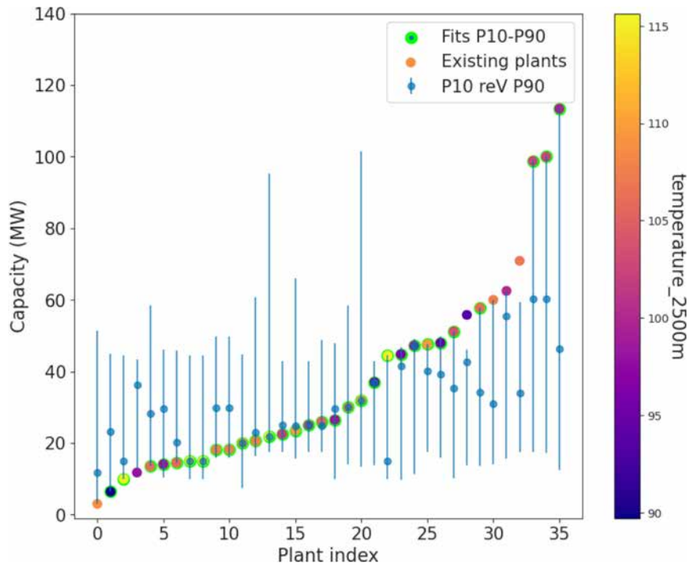
IMPACT: Increasing certainty in the development of new geothermal plants by providing detailed assessments of estimated geothermal resources with grid infrastructure and land use characteristics.

In FY24, NREL completed year 2 of a 3-year portfolio of Modeling and Analysis Projects to understand geothermal value to a decarbonized energy economy and improve representation in flagship NREL tools.

ENHANCED REPRESENTATION OF GEOTHERMAL POWER POTENTIAL IN reV MODEL

Modeling the potential future deployment of renewable energy generation requires minimizing costs and maximizing power production, while also considering siting constraints, environmental and ecological impacts, and social acceptance from local communities. This is a challenging optimization that has been represented between two NREL models: the Renewable Energy Potential (reV) model and the Regional Energy Deployment System (ReEDS). FY23 work in the Geothermal Analysis Portfolio began the task of reporting geothermal technologies with an appropriate fidelity equal to that of wind and solar. NREL'S new reV geothermal module developed in FY24 allows for several data types to be input as geothermal resource potential: discrete points of geothermal plant performance and depth discrete temperatures. The reV geothermal module allows for detailed assessment of the geospatial intersection of the estimated geothermal resource with grid infrastructure and land use characteristics.

However, geothermal resources are very different from wind and solar resources, requiring novel representations of the generation potential. The geothermal module in reV has continued to improve the representation of geothermal resources. This focus represents the novelty of the project, as it is the first time that resource uncertainty will be modeled in reV. The 10th and 90th percentile geothermal capacity estimates (blue ranges in the figure below) are now also represented by using machine learning and many geological and geophysical data layers from the INGENIOUS project, along with operating power plants (colored circles).



Nameplate capacity of 36 geothermal power plants in the Great Basin, plotted in ascending order. Blue vertical lines represent the colocated 10th percentile (P10) and 90th percentile (P90) estimates by machine learning algorithms. These P90 and P10 estimates are predicted throughout the Great Basin region to represent the geothermal potential uncertainty. *Graphic by NREL*

RESEARCH AND DEVELOPMENT HIGHLIGHTS: GRID INTEGRATION RESEARCH PILLAR

Geothermal Analysis Portfolio

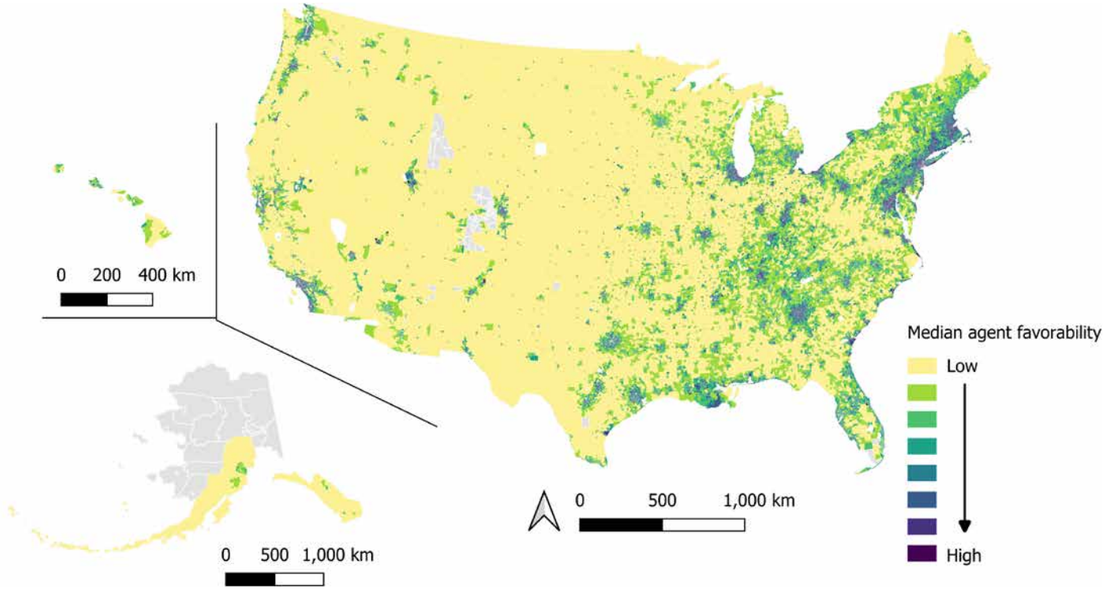
PRINCIPAL INVESTIGATOR:
Koenraad Beckers

IMPACT: Providing a better estimate of the nationwide potential of using geothermal heat pumps, ambient temperature loops, and direct use for heating and cooling in the United States could help planners, policymakers, and other stakeholders in decarbonization planning.

dGEO IMPROVES ACCURACY OF GEOTHERMAL POTENTIAL PREDICTIONS

The Distributed Geothermal Energy Simulation Tool (dGeo) is an NREL-developed tool designed to explore the potential role of geothermal distributed energy resources in meeting thermal energy demands in the United States. In FY24, an NREL research team updated dGeo with several new features designed to improve estimates of potential geothermal heat pump (GHP) and direct use cases. This included providing more accurate predictions of the technical, economic, and market potential of geothermal heat pumps, ambient temperature loops (sometimes referred to as thermal energy networks), and deep direct use for the United States through 2050. Updates also took into account the latest thermal demand, while expanding the tool to Alaska and Hawai'i and updating geothermal resource maps.

The tool now has the capability to simulate ambient temperature loops and features upgraded GHP modules that utilize GHEDesigner and building stock data via ResStock and ComStock. Finally, researchers upgraded the underlying framework from the 2010 to the 2020 census tract. The first half of FY24 focused on model updates, while the second half focused on new model runs updating the GeoVision results and showing new GHP, ATL, and DU adoption curves for the United States. The updates allow simulations for all 50 states and reflect the latest cost, demand, resource, price, and performance data.



Example dGeo results map showing median agent net present value (NPV) across the United States for geothermal ambient-temperature loops. *Graphic by Juliet Simpson, NREL*

RESEARCH AND DEVELOPMENT HIGHLIGHTS: GRID INTEGRATION RESEARCH PILLAR

Geothermal Analysis Portfolio

PRINCIPAL INVESTIGATOR:
Weijia Liu

IMPACT: Enhancing NREL's power system analysis capabilities and techno-economic and capacity expansion modeling, allowing for more accurate production cost models.

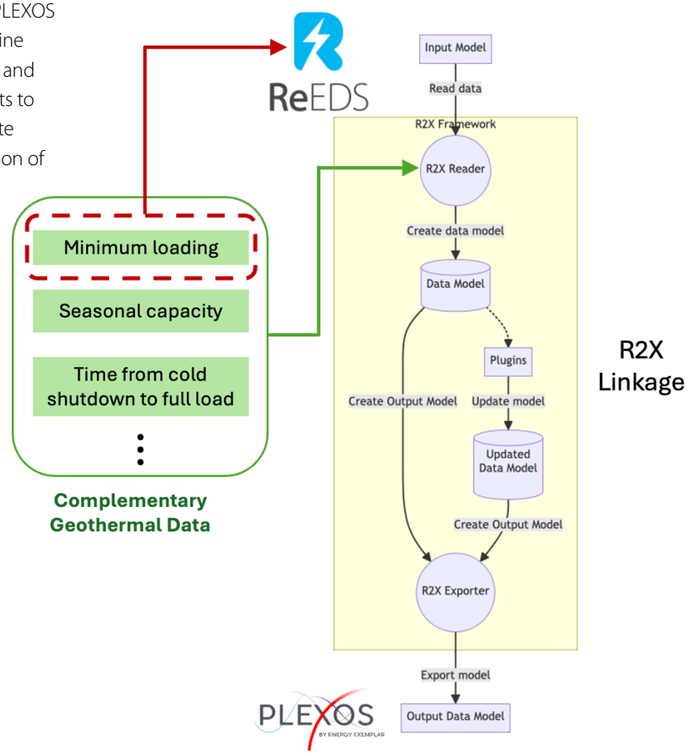
IMPROVING GEOTHERMAL POWER IN PLEXOS

NREL uses a robust suite of modeling tools as part of its power system analysis capabilities. Substantial work has been done to improve a number of these models including ReEDS, dGeo (a variant of the dGen), and the Renewable Energy Potential Model (reV). These developments have improved the capacity expansion model representations of geothermal power. In FY24, NREL focused on improving the existing model translation tool for PLEXOS to build more accurate production cost models (PCM).

For this project, the team primarily worked on two tasks. The first was to identify key technology performance characteristics for geothermal power (plant size, ramp rate, etc.) for inclusion with ReEDS and PLEXOS PCM. The second task was to examine current geothermal representation and implement identified improvements to the modeling linkage with complete simulation validation and comparison of new capabilities.

This project focused on strengthening the R2X (ReEDS to PLEXOS model translation) capability that underlies the linked ReEDS and PLEXOS analysis. The result is an improved linkage tool with enhancements implemented based upon the advice of power technology experts.

This new modeling tool will be used for future ReEDS-PLEXOS analysis, which includes many flagship NREL studies as well as ReEDS standard scenarios. Documentation of the improvements will be released as an NREL technical report and provide a comprehensive detail of best practices for representing geothermal in PCMs.



An example of the production cost modeling NREL has developed in PLEXOS. *Graphic from Pedro Andres Sanchez Perez*

Geothermal Analysis Portfolio

PRINCIPAL INVESTIGATOR:
Tom Harris

IMPACT: An array of geothermal bulk power and thermal energy generation technologies are now available in Engage and ready for use by Engage modelers in geographic locations where geothermal resource data sufficient for GEOPHIRES configuration is available.

HSEO Hawai'i Engage modeling shows that, with current assumptions, further expansion of geothermal bulk power generation is economically viable.

ENGAGE™ CAPACITY PLANNING WEB APPLICATION

Engage is NREL's free, public, map-based web application that models energy systems with high shares of variable generation from district energy systems and microgrids to countries and continents. Engage facilitates collaborative cross-sectoral energy system planning and simulation integrating electricity, thermal energy, fuels, water and other commodities with engaging visualizations.

In FY24, NREL enhanced Engage with the addition of templates representing geothermal technologies, including hydrothermal and EGS coupled with power conversion technologies (binary Organic Rankine Cycle (ORC), flash, double flash), direct use, combined heat-and-power, and combined cooling-heating-and-power. GEOPHIRES is integrated to estimate cost and capacity relationships for the technologies; the FY24 work updated costs in GEOPHIRES to harmonize with those in Geothermal Electricity Technology Evaluation Model and System Advisor Model.

Engage is used by the Hawai'i State Energy Office (HSEO) for grid integration and decarbonization modeling. In FY24, NREL upgraded the HSEO Engage decarbonization scenarios to accommodate further capacity expansion of geothermal bulk power generation on the Island of Hawai'i and to investigate economic feasibility of geothermal bulk power generation on the islands of O'ahu and Molokai. The Engage models incorporated geothermal energy technical potential data from the NREL Renewable Energy Potential Model (reV) for hydrothermal binary ORC. Hawai'i Engage modeling shows that, with current assumptions, further expansion of geothermal bulk power generation is economically viable and competitive.

engage

PRINCIPAL INVESTIGATOR:
Matt Mitchell

IMPACT: Providing a first-of-its-kind set of free, open-source tools for simulating and screening ground-source heat pump systems.

PARTNERS:
Ladybug Tools

GROUND-SOURCE HEAT PUMP SYSTEMS ADDED TO URBANopt PLATFORM FOR DISTRICT SYSTEM MODELING

NREL developed modeling tools for district-connected geothermal heat pump systems in URBANopt™, NREL's advanced analytics platform for high-performance buildings and energy systems within one geographically cohesive area.

Completing the second year of work on this project, the NREL team has built on the initial functionality to introduce new features within these modelling capabilities. A pilot study was also set up with industry partners to exercise those capabilities and provide a pathway for collecting feedback and integrating it back into the tool. New features include life-cycle cost analysis calculation and integration of physics-based pipe models to simulate the physical storage aspect of the pipes used in ground-source heat pump systems, as well as capabilities for estimating heat loss or gains from soil.

URBAN OPT

Geothermal Analysis Portfolio

PRINCIPAL INVESTIGATOR:
An Pham

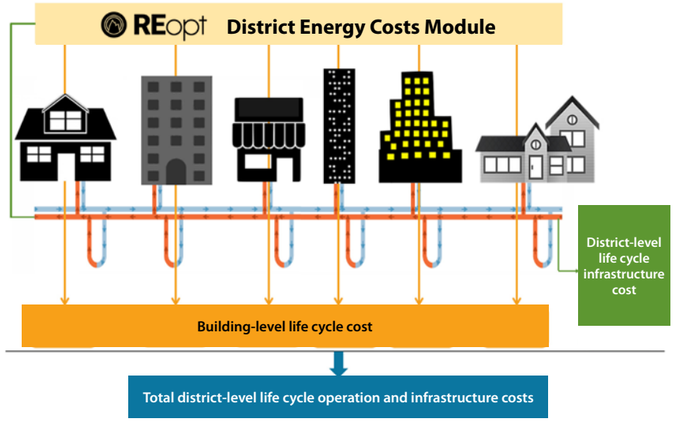
IMPACT: Expanding the capabilities of both REopt and URBANopt, enabling life-cycle cost analysis for district GHP and GHX systems modeled by URBANopt.

ADDING CO-SIMULATION CAPABILITIES BETWEEN REopt AND URBANopt FOR COST ANALYSIS OF NETWORKED OR DISTRICT GEOTHERMAL HEATING AND COOLING

NREL has developed a District Energy Costs (DEC) Module that allows for integration in both REopt® and URBANopt, renewable energy integration and optimization web tools, to enable life-cycle cost (LCC) analysis considerations to be included in system design decisions for networked geothermal heat pump (GHP) systems. With the finalization of the DEC module, URBANopt users can call REopt API to perform LCC analysis of URBANopt's district GHP system.

The DEC Module takes GHP and ground heat exchange (GHX) sizing and dispatch outputs from URBANopt as inputs and calculates life-cycle capital and operation cost for each URBANopt-specified building and URBANopt-specified district GHP and shared (GHX) systems. The DEC Module then calculates the total district-level capital and operation LCC of investment in an URBANopt-specified district GHP/GHX system as the sum of the LCCs of all URBANopt-specified buildings and URBANopt-specified shared GHP and GHX infrastructures.

A newly developed district energy costs module in REopt enables district-level life-cycle cost analysis. *Graphic by NREL*



A newly developed district energy costs module in REopt enables district-level life-cycle cost analysis. *Graphic by NREL*

GEOTHERMAL HEAT PUMPS FOR THE U.S. BUILDING STOCK

The ComStock and ResStock tools model existing commercial and residential building stock at a detailed geographic and temporal resolution, an ensemble of nearly one million individual physics-based building energy models that statistically represent a majority of the commercial and residential building stock in the United States. ComStock and ResStock ask and answer two questions: How is energy used in the U.S. building stock and what is the impact of energy-saving technologies? The datasets identify where energy is being consumed geographically, in what building types and end uses, and at what times of day. Simultaneously, they identify the impact of efficiency and electrification measures.

These tools have the capability to model GHP systems as they perform in the U.S. building stock, allowing for scenario analysis to consider adoption, next-generation system performance, and potential benefits. Incorporating GHP modeling into ComStock and ResStock allows users to create projections of different technology scenarios and large-scale decarbonization impact analyses. This also allows data integration with other tools, feeding bulk power system models with building energy consumption annual and time series data about future building stock scenarios with geothermal heat pump (GHP) systems.

With a total of 3,000 user accounts linked to the data viewer for ComStock and ResStock, incorporating

RESEARCH AND DEVELOPMENT HIGHLIGHTS: GRID INTEGRATION RESEARCH PILLAR

Geothermal Analysis Portfolio

geothermal technologies into this database has the potential to showcase GHP potential to a new audience. Upgrades to GHP modeling in ComStock and ResStock FY24 include: modeling three GHP-served HVAC system configurations for commercial buildings, including retrofits for rooftop units (the most common HVAC system in commercial buildings), hydronic systems, and various ductless systems. For residential buildings, one GHP-served HVAC configuration was modeled and paired with envelope improvements and electrification measures to analyze the impact of various measure packages. The GHP upgrade measures were run against the baseline ComStock and ResStock and the energy, peak, emissions, and utility cost impacts are being analyzed. The full dataset of results was released as part of the End Use Savings Shapes dataset release in March 2024.

ComStock

ResStock

LEARN MORE

bit.ly/46oyR0k

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bit.ly/4dB96N5

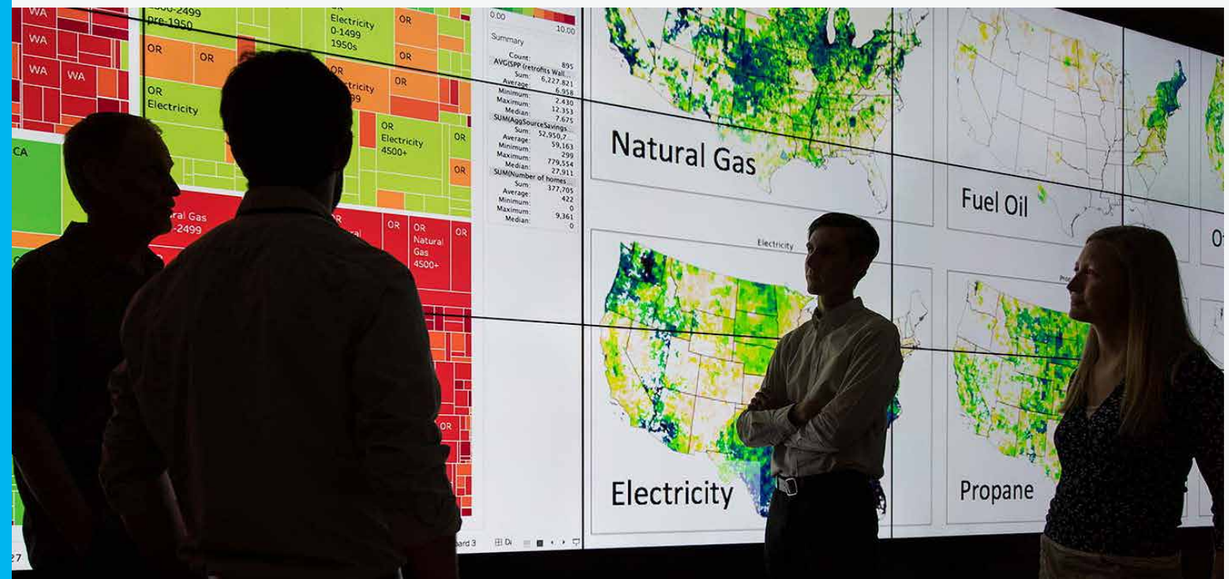
bit.ly/4cXHm5h

PRINCIPAL INVESTIGATOR:
Marlena Praprost

IMPACT: Including geothermal technologies in building stock modeling programs illustrates where GHPs have the potential to be most impactful, and how they can work with other building technologies to aid in decarbonization.

PARTNERS: The team would like to thank the Technical Advisory Group members, made up of 15 organizations spanning government, academia, and industry, for their valuable feedback and input throughout the project.

Researchers review the ResStock analysis tool, which helps states, municipalities, utilities, and manufacturers identify which home improvements save the most energy and money. *Photo by Dennis Shroeder, NREL*



RESEARCH AND DEVELOPMENT HIGHLIGHTS: GRID INTEGRATION RESEARCH PILLAR

Geothermal Analysis Portfolio

NATIONAL GEOTHERMAL HEATING AND COOLING EXPANSION ANALYSIS

The FY24 Geothermal Heat Pump **Impact Analysis** add answered questions relevant to how much investment costs change with a hypothetical mass adoption of GHPs. Building off that analysis, the National Geothermal Heating and Cooling Expansion Analysis performed a comparison against different types of geothermal upgrades, such as GHPs and geothermal heating and cooling. Utilizing ResStock™ and ComStock™ data, NREL's team examined the impact of moving from fuel-based technology to electrifying with a more efficient source, taking into consideration the entire benefits system from overall cost to occupant health.

PRINCIPAL INVESTIGATOR:
Jonathan Ho

IMPACT: This analysis allows researchers to look at the broader, cumulative picture of how the grid is impacted by enabling new technology, as well as address questions related to the value of certain technology upgrades.

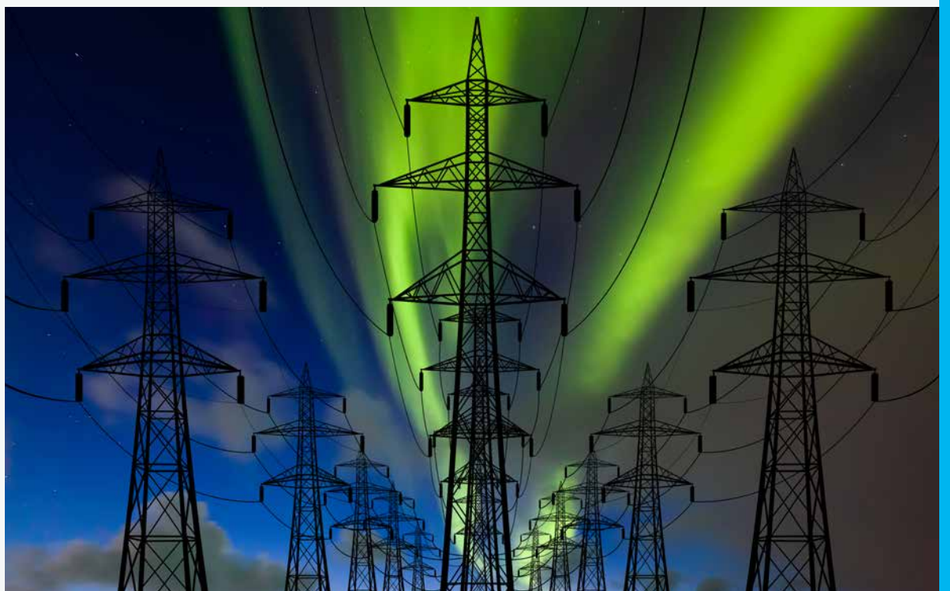
PRINCIPAL INVESTIGATOR:
Jonathan Ho

IMPACT:
Exploring how services provided by underground seasonal geothermal storage systems impact the grid, and their value, could help advance co-deployment of this cutting-edge technology with more conventional geothermal technologies.

UNDERSTANDING THE VALUE OF UNDERGROUND THERMAL STORAGE TO POWER SYSTEMS

How much value is added to a power system with the addition of underground thermal energy storage (UTES) capable of powering, heating, and cooling the grid through changing seasons? An NREL project worked to understand exactly that. The research team considered how much stakeholders value these energy storage characteristics and how it may impact the costs of building new plants. This provided a window into understanding what the economically justifiable range of costs would be in order to see deployment and utilization of UTES features.

High voltage towers at the northern lights background. Power lines against the polar sky. *Getty image 1322973512*



LABORATORY INVESTMENT IN GEOTHERMAL RESEARCH CAPABILITIES

NREL INVESTMENT IN GEOTHERMAL RESEARCH CAPABILITIES

GEOTHERMAL HEAT PUMP MODELING FOR SOUTH TABLE MOUNTAIN ENERGY PARK

PRINCIPAL INVESTIGATOR:
Michelle Slovensky and Saqib Javed

NREL's newly acquired South Table Mountain Energy Park (STEP) will convert a former military base into a technology hub to explore renewable energy applications needed to catalyze the latest research and products closer to commercialization. Formerly known as Camp George West, this site was used for military training programs throughout World War II, and in 1993 was listed on the National Register of Historic Places.

The exteriors of the barrack structures will remain but the interiors, building equipment, and site infrastructure will be redeveloped. This is a wonderful opportunity to showcase the reuse of buildings retrofitted with advanced energy systems to optimize performance and replication strategies. To envision an implementation approach, NREL researchers assessed the potential of geothermal heat pumps for campus heating and cooling through modeling and simulation. Because the STEP campus is positioned to be a demonstration site that convenes collaborative research by government, industry, and startups, its solutions should reflect advancements in technology innovation. The team investigated various design scenarios, including a centralized borefield for all buildings, individual borefields for the buildings, and decentralized borefields connected through a thermal energy network for energy sharing between buildings. The work also incorporated a phased modularity approach given that construction of building facilities is dependent on mission growth and capital funding.

Integrating operational processes for performance and maintenance influences the technology development and provides feedback to industry partners who are working on gaps in this sector space.

South Table Mountain Energy Park, formerly known as Camp George West, neighboring the NREL STM Campus. *Photo by Dennis Schroeder, NREL*

SOUTH TABLE MOUNTAIN CENTRAL PLANT GEOTHERMAL

PRINCIPAL INVESTIGATOR:
Michelle Slovensky

In FY24, NREL researchers investigated converting the existing natural gas-supplied central plant heating system to non-carbon fuel sources at the NREL South Table Mountain campus. Non-carbon fuel sources could include geothermal heat pumps (GHPs) for heating and cooling.

The team collected historical operations data from NREL Site Operations and used this as a baseline for modeling a transition to geothermal-based heat pump system. The team developed EnergyPlus® models of the central campus heating system, and then made first approximations of the number of boreholes needed to operate the system.

Additional studies explored coupling geothermal with waste heat recovery from ESIF's High Performance Computation Data Center (HPCDC) to optimize the district heating system of the campus. Such a system would allow for in-ground summertime storage of heat from the HPCDC that could then be used during the heating season. Likewise, the borefield would cool over the winter months and could be leveraged as a cooling resource in the summer.

Using on-campus thermal resources provides an efficient way to work toward campus decarbonization and facility electrification without over-reliance on grid-supplied, carbon-intense electricity.

Aerial view of the National Renewable Energy Laboratory (NREL) South Table Mountain (STM) campus from the east entrance. *Photo by Joshua Bauer and Bryan Bechtold, NREL*

GEOTHERMAL SHOWCASE: GEOTHERMAL HEAT PUMP SYSTEM ON MESA TOP CAMPUS

PRINCIPAL INVESTIGATOR:
Xiaofei Pu

Building off a GTO-supported 2011 installation, FY23 and FY24 NREL investments were made to advance the Geothermal Showcase project, which features a GHP system that heats and cools the Solar Research Radiation Laboratory (SRRL) on NREL's Mesa Top Campus in Golden, Colorado.

The system consists of 23 boreholes at a depth of 300 feet depth with varying insulation and configurations (e.g., double U-tube). It was engineered to operate with full heat load 24 hours a day, 365 days a year, and to monitor the system performance, including subsurface heat transfer.

In FY24, power meters for 17 components of the GHP system were installed and connected to the data logging system, paving the way for monitoring and modeling long-term performance of the system. Maintenance and repair of down-borehole temperature sensors systems will also revive a dozen that will be connected to the data logging system.

In FY25, a GTO funded project will support additional instrumentation installation intended to capture subsurface information, performance monitoring and analysis, as well as the design of an educational program based on live data from the GHP system to demonstrate the benefit of geothermal technologies.

STRATEGIC PARTNERSHIPS

GEOTHERMAL STRATEGIC PARTNERSHIPS IN FY24

The NREL geothermal team has several ongoing strategic partnership projects (SPP) in FY24 with industry and non-DOE government agencies, including the Department of Defense, Department of the Interior, utilities, and others.

U.S. DEPARTMENT OF DEFENSE: U.S. AIR FORCE AND U.S. ARMY

The NREL geothermal team provides technical assistance to the Department of Defense, including the U.S. Air Force and the U.S. Army. Several military bases are considering utilizing geothermal energy to provide reliable baseload and dispatchable electricity and heating. The NREL team assists the Department of Defense by providing third-party evaluation of geothermal technologies for deployment at their military bases.

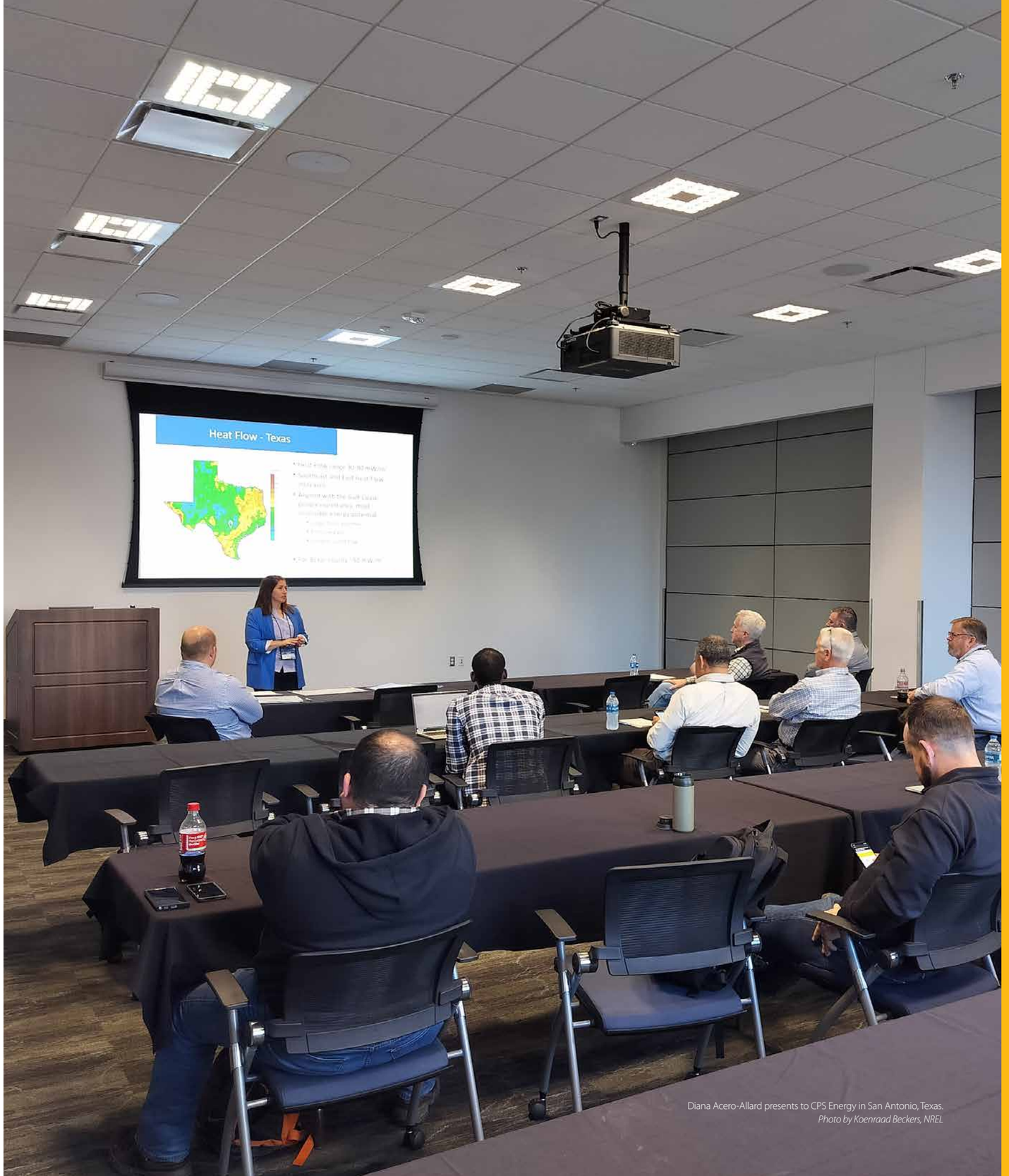
U.S. DEPARTMENT OF THE INTERIOR: BUREAU OF LAND MANAGEMENT

The NREL geothermal program has a longstanding partnership with the Bureau of Land Management (BLM) and has provided subject matter expertise to BLM on multiple geothermal topics. Examples of projects include development of geothermal training materials for BLM personnel, development of inspection and enforcement documents, and maintenance of a database of geothermal wells on federal lands, including operating, idle, and abandoned wells. In FY24, the fact sheet on geothermal energy was significantly updated to include new graphics, such as a project development timeline and visual explanation of geothermal technology basics. The fact sheet is used by BLM at conferences and events to show general information about geothermal energy, market outlook, usage and economic contributions, land disturbance, and leasing and permitting basics.

CPS ENERGY IN SAN ANTONIO, TEXAS

NREL partnered with CPS Energy in San Antonio, Texas, to investigate feasibility and opportunities to utilize geothermal energy in their region. Tasks included local geothermal resource assessments, evaluating feasibility of different geothermal technologies for electricity generation for local subsurface conditions, a workshop with CPS Energy leadership in March 2024, and general subject matter expertise to support CPS Energy on local geological conditions and geothermal potential.

During the workshop researchers presented results of the analysis and how geothermal could be part of CPS' new energies portfolio to achieve San Antonio's goal of carbon neutrality by 2050.



Diana Acero-Allard presents to CPS Energy in San Antonio, Texas.
Photo by Koenraad Beckers, NREL

Geothermal Strategic Partnerships in FY24

CON EDISON IN NEW YORK CITY

NREL is working with Con Edison, a utility in New York City, on a geothermal district heating feasibility study. Con Edison runs the largest steam-based district heating system in the world and has partnered with the NREL geothermal team to investigate decarbonizing the heating system using geothermal technologies.

NREL has completed a resource assessment of deep geothermal resources (estimating the local geothermal gradient and lithological investigations), as well as preliminary reservoir and surface plant integration simulations. Future work involves an assessment of shallow geothermal resources and technologies, techno-economic analysis of several technology options, and providing guidance on permitting, well siting, and logistical challenges.

IDP ENERGY IN GRAND SKY, NORTH DAKOTA

In FY24 NREL investigated the feasibility of utilizing geothermal boreholes coupled with heat pumps and augmented with natural gas-fired heating to provide heating and cooling to the Grand Sky development project near the Grand Forks Air Force Base in North Dakota for IDP Energy.

NREL combined hourly heating and cooling loads, available footprint for well drilling, and thermal response test data with GHEDesigner modeling to size a vertical geothermal borehole field. Researchers estimated capital and operation and maintenance costs to evaluate the net present value of this system.

By comparing with a baseline HVAC system (natural gas for heating and air-cooled chillers for cooling), NREL evaluated cost-competitiveness and techno-economic feasibility of the GHP system.

THE PORT AUTHORITY OF NEW YORK AND NEW JERSEY

The Port Authority of New York and New Jersey (PANYNJ)—a joint venture between the states of New York and New Jersey with headquarters in New York City—has contracted a multidisciplinary NREL team to assist in designing a replacement for the busiest bus terminal in the world, the Port Authority Bus Terminal in midtown Manhattan. The NREL geothermal team is tasked with investigating options for utilizing geothermal energy for heating and cooling the bus terminal.

Work includes conducting a local resource assessment, evaluating feasibility of different types of geothermal energy for supplying the thermal demand, and providing guidance on the geothermal development process including reviewing necessary permits. The NREL team is currently evaluating different geothermal technologies such as shallow borehole heat exchangers, standing column wells, and deep direct-use systems.

Test borehole for the LeGUp project in Lowell, Massachusetts. *Photo by Juliet Simpson, NREL*

Ribbon cutting for the LeGUp geothermal network demonstration project in Massachusetts. Framingham Mayor Charlie Sisitsky and Eversource President, CEO, and Chairman Joe Nolan cut the ribbon. From left: Nikki Bruno, Eversource Vice President for Customer Experience and Energy Strategy, Massachusetts Secretary of Energy and Environmental Affairs Rebecca Tepper, Charlie Sisitsky, Joe Nolan, HEET Co-Executive Director Zeyneb Magavi, and President of Eversource Gas Bill Akley. *Photo from Eversource*

LeGUp—GEOTHERMAL NETWORKS DEMONSTRATION

Through support from the state of Massachusetts, members of the NREL geothermal team are partnering with the nonprofit HEET on the Learning from the Ground Up (LeGUp) project, studying the first utility-led geothermal networks demonstration in Massachusetts as a pathway to decarbonize heating and cooling. The first round of installation in Framingham, Massachusetts, is complete and the system is expected to start operation in 2024, while the second demonstration in Lowell, Massachusetts, is in the design phase with test boreholes completed.

Geothermal network systems include a thermal network that links each building, water-source heat pumps connected to the loop for meeting user heating and cooling loads, and geothermal borehole fields. The LeGUp team is analyzing these installations and considering technical and economic performance along with environmental, health, and equity impacts. As part of this project, NREL is developing a reduced-order model for the thermal loop, connected buildings, and borehole fields to capture the movement of heat around the network, the use of electricity, and the system costs.

These modeling efforts will allow the group to better understand operation strategies of these pilot installations and then improve performance and reduce costs for future installations.

INDUSTRY LEADERSHIP

LEADERSHIP IN THE GEOTHERMAL SECTOR

NREL-HOSTED WORKSHOPS

Geothermal Power Systems Analysis Workshops

The NREL geothermal program held two successful workshops in January and August to advance modeling of geothermal power systems through stakeholder input. At the January workshop, 70 invited attendees, representing developers, operators, investors, regulatory agencies, system modelers, national laboratory researchers, consultants, and other stakeholders, met to workshop current assumptions and approaches on techno-economic, resource assessment, and deployment scenarios when modeling geothermal technologies. NREL researchers Matthew Prilliman, Brian Mirletz, Erik Witter, Jonathan Ho, Whitney Trainor-Guitton, Paul Pinchuk, and Travis Williams presented current modeling capabilities and methodology and held breakout room discussions to identify updates that would best serve the entire geothermal industry.

Led by Dayo Akindipe, the workshops focused on hydrothermal and enhanced geothermal systems tied to flash or binary cycles. The first day of the January workshop covered geothermal techno-economic modeling in the Geothermal Electricity Technology Evaluation Model (GETEM) and the System Advisor Model (SAM) for the Annual Technology Baseline (ATB). The second day focused on estimating geothermal resource availability in the Renewable Energy Potential (reV) model and modeling future deployment scenarios with the Regional Energy Deployment System (ReEDS). Due to the success of the January workshop, a follow-up workshop was requested in August 2024, where more elaborate discussions around the outcomes of the 2024 ATB effort and areas for further improvements to the geothermal power model assumptions took place.

Geological Thermal Energy Storage (GeoTES) Workshop

NREL hosted a two-day hybrid workshop, April 29–30, 2024, to discuss outcomes from multiyear research and development efforts related to GeoTES across national laboratories and industry partners. GeoTES utilizes underground reservoirs to store and dispatch energy per a given demand schedule that can span an entire season. The workshop discussed the technical and economic considerations for GeoTES technology commercialization. Technologies presented were solar thermal coupled with GeoTES in depleted oil and gas reservoirs and the coupling of heat pumps charged by excess renewable electricity with GeoTES in shallow reservoirs.

The 30+ participants at the workshop were from DOE, the U.S. Geological Survey, other national laboratories, industry, and state agencies. NREL's research on GeoTES provides data and analysis to stakeholders and decision-makers on the potential of GeoTES for long-duration energy storage and its technology and market readiness to participate in the accelerating the renewable energy market.

Researchers from multiple national laboratories joined together for the GeoTES workshop in April 2024 on the NREL campus. *Photo by Guangdong Zhu, NREL*

GEOPHIRES Workshop

On July 18, Koenraad Beckers led a workshop on GEOPHIRES, a free NREL software that runs techno-economic simulations for geothermal energy systems. This workshop brought together GEOPHIRES users, developers, GTO, and other stakeholders. Participants discussed the latest updates, examined case studies, walked through a demonstration, and held a roundtable discussion on desired future features in GEOPHIRES. Particular areas of focus included coding best practices, academic application of course material, GitHub changes, and more.

Leadership in the Geothermal Sector

NREL HOSTS ICELANDIC GEOTHERMAL DELEGATION

On June 21, 2024, NREL was honored to host delegates from Iceland's Ministry of the Environment, Energy, and Climate and others during their trip to Colorado to take part in the Colorado-Iceland Clean Energy Summit on June 20. During the delegation's visit, they toured the Field Test Laboratory Building and the Energy Systems Integration Facility and heard from NREL Director Martin Keller and Associate Laboratory Director Johney Green about current NREL priorities and strategies, and from geothermal program leadership about NREL's geothermal research and development activities. The delegation explored opportunities for U.S.-Iceland R&D Collaboration on geothermal energy, green hydrogen, and carbon capture, utilization and storage (CCUS).

COLORADO-ICELAND CLEAN ENERGY SUMMIT

NREL supported the Colorado-Iceland Clean Energy Summit, co-organized by the US Icelandic Embassy and the State of Colorado, on June 20, 2024.

Hosted by the State of Colorado, Denver Economic Development & Opportunity, the Embassy of Iceland, and Green by Iceland, the conference was meant to strengthen cooperation between Colorado and Iceland in the fields of geothermal energy and carbon capture utilization and storage solutions. NREL Geothermal Program Manager Amanda Kolker spoke on a panel on energy streams from geothermal power plants and cascaded use.

Amanda Kolker speaks on a panel at the Colorado-Iceland Clean Energy Summit on June 20, 2024. *Photo from the Embassy of Iceland*

Leadership in the Geothermal Sector

CONFERENCES

20 Talks at Largest Geothermal Rising Conference to Date

Eighteen members of NREL's geothermal team participated in the Geothermal Rising Conference from October 1–4, 2023, in Reno, Nevada, with more than 1,600 total attendees. The conference was the largest to date and featured 20 talks from NREL researchers, ranging from methods to reduce geothermal development risk, advances in superhot geothermal, oil and gas applications, and more.

NREL Geothermal Program Manager Amanda Kolker was part of the opening plenary panel and discussed "Energizing Equity: Fostering Diversity of Resources, Inclusion of Stakeholders, and an Equitable Energy Future for All." NREL also hosted a booth at the event, interfacing with hundreds of visitors and representing DOE and NREL geothermal programs and research. **The NREL FY23 Geothermal Accomplishment Report** was the highlight of the booth and was provided to 150 attendees.

NREL Geothermal Part of the American Association of Petroleum Geologists' Inaugural "New Energy from Subsurface Fuels" Conference

The American Association of Petroleum Geologists and Geothermal Rising hosted the Geothermal, Lithium, Hydrogen: New Energy from Subsurface Fluids Conference in Houston, Texas, in June 2024. This was the first time the Association and Geothermal Rising brought together geothermal energy, critical minerals, storage, and hydrogen at a national conference attended by experts from across the country. NREL Geothermal Program Manager Amanda Kolker, delivered a presentation titled "Improving Geothermal Economics through Added Value Streams: Mineral extraction and H2 & Energy Storage" that highlighted NREL work in those multiple domains. She also served on a panel focused on identifying opportunities and challenges of combining geothermal energy production with energy storage and mineral extraction.

NREL geothermal team at the 2023 Geothermal Rising Conference in Reno, Nevada. *Photo by NREL*

Leadership in the Geothermal Sector

2024 was the first year NREL was represented at the GEOLAC conference. *Photos from GEOLAC*

NREL Participates in 10th Geothermal Congress for Latin America and the Caribbean Conference in Colombia

NREL was invited to the 10th **Geothermal Congress for Latin America and the Caribbean** (GEOLAC) conference in Cartagena, Colombia, on Nov. 28–29, 2023. Amanda Kolker delivered a presentation titled "U.S. Perspective: Can Geothermal Enter the Energy Mainstream?"

The goal of the conference is to bring together government, industry, academia, and other stakeholders to address regionwide development challenges and opportunities for geothermal in Latin America and the Caribbean.

Stanford Geothermal Conference

Eight NREL geothermal researchers attended the 49th **Stanford Geothermal Workshop** in Palo Alto, California, from Feb. 12–14, 2024. The conference was the largest to date and featured 20 talks from NREL researchers, ranging from geothermal technology and resource modeling to policy and market analysis and more.

The Stanford Geothermal Workshop is a yearly technical event focused on geothermal research and innovation, gathering academic institutions, labs, and industry for nearly 50 years. The NREL geothermal team presented NREL's latest analyses and projects, gathering valuable feedback and insight from peers.

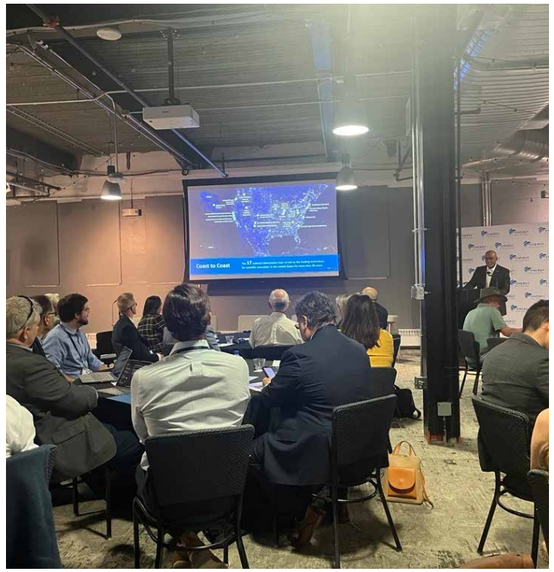
A social media post from the Stanford Geothermal Conference in February 2024. *Graphic by NREL*

Leadership in the Geothermal Sector

NREL Geothermal Part of Inaugural Geothermal Rising Thermal Energy Networks Symposium

Faith Smith and Koenraad Beckers represented NREL at the Geothermal Rising **Thermal Energy Network Symposium** on March 12–14, 2024, in Rochester, Minnesota. Faith presented a preview of the markets and policy information that will be included in the 2025 Market Report. Specifically, she discussed the different state-level incentives and programs available for all geothermal technologies as well as utility-level rebates for geothermal heat pumps. The audience—primarily investors and developers—had positive reactions to NREL's database on incentives and programs available for their projects. Based on interactions from the event, additional industry data is being collected to update NREL's thermal energy network modeling tools.

Faith Smith presents at the Thermal Energy Network Symposium in Rochester, Minnesota. *Photo courtesy of Koenraad Beckers, NREL*



Johney Green, NREL associate laboratory director, presents at the Colorado Energy Office event. *Photo by Amanda Kolker, NREL*

Energy Dialogues and Colorado Energy Office Event

In fall 2023, NREL associate laboratory director for Mechanical and Thermal Energy Sciences Johney Green and NREL Geothermal Program Manager Amanda Kolker presented at an invitation-only event in Denver organized by the **Colorado Energy Office** and **Energy Dialogues** to bring together geothermal thought leaders. The event, "Harnessing Earth's Heat: Geothermal Energy and Carbon Management Dialogue," convened dozens of leaders to discuss the potential of geothermal energy in Colorado, its applications in carbon management, and near-term opportunities in geothermal deployment. Green gave opening remarks for the event, speaking about NREL's research mission and the potential for geothermal technologies to play a larger role in national decarbonization goals. Amanda moderated a panel on shallow geothermal resources and technologies, and Governor Polis provided closing remarks highlighting recent efforts by the State of Colorado to facilitate geothermal development.

EXPANDED STAKEHOLDER ENGAGEMENT AND OUTREACH

PUBLICATIONS **HIGHLIGHTS**

NEW PUBLICATION HIGHLIGHTS TECHNO-ECONOMIC FEASIBILITY OF REPURPOSING INACTIVE OIL AND GAS WELLS FOR GEOTHERMAL DISTRICT HEATING AND COOLING IN TUTTLE, OKLAHOMA

A new paper featured in ***Energy Conversion and Management*** by researchers Hyunjun Oh, Sertac Akar, Koenraad Beckers, Eric Bonnema, and colleagues at the University of Oklahoma, describes how inactive oil and gas wells can be repurposed for geothermal district heating and cooling. This paper evaluated geothermal resources, heating and cooling demand, and techno-economic potential of four oil and gas wells for geothermal heating and cooling in two public schools and 250 nearby houses in Tuttle, Oklahoma. The study found that use of a system of repurposed oil and gas wells was cost-competitive with the regional natural gas rate. Further, recycling existing oil and gas wells would result in $7 million cost savings compared to drilling a dedicated geothermal borefield for the district energy system.

DE-RISKING SUPERHOT EGS DEVELOPMENT THROUGH 3D PLAY FAIRWAY ANALYSIS

NREL researchers Nicole Taverna, Hannah Pauling, Whitney Trainor-Guitton, Amanda Kolker, and Geoffrey Mibei published an article in Geothermics called **"De-risking superhot enhanced geothermal system (EGS) development through 3D play fairway analysis."** The article described the methodology developed in the DEEPEN project for derisking superhot EGS (see writeup, p. 10) and its application at a superhot EGS site in Oregon, USA. De-risking superhot EGS development will help meet the DOE Earthshot goal of geothermal power at < $45/MWh and fulfill the federal government's goal of a carbon-free electric grid by 2035. By modifying Play Fairway Analysis for superhot geothermal targets, the method can be expanded past its current limits.

NREL PUBLICATION UTILIZES 3D UNCERTAINTY MODELLING FOR GEOTHERMAL WELL SITING

How do technicians decide where to drill next in geothermal exploration? Prospecting for hidden geothermal resources can be challenging and expensive, and target goals can vary from locations with the highest probable economic temperatures to areas where uncertainty is highest. A **new paper featured in *Geoenergy*** led by NREL geoscientist Whitney Trainor-Guitton provides methodologies using 3D temperature uncertainty modeling and metrics that address these well-siting goals, while also potentially aiding in cost and energy savings. The paper utilizes existing temperature and structural geology information around Granite Springs Valley, Nevada, to explore methodologies using stochastic, spatial statistics to match all existing temperature data and adhere to structural information such as faults, dilation tendency, and Coulomb stress. Using these refined methods, drilling budgets can be optimized and uncertainty in drilling locations reduced.

NREL and Gradient Geothermal researchers inspect production well at Blackburn field in Nevada.
Photo by Koenraad Beckers, NREL

Communications

MEDIA MENTIONS

2,412 media hits related to NREL and geothermal

~3,858,266,800 individuals reached

The San Diego Union Tribune
Turning California's oil fields into energy storage sites
August 14, 2024

"The thinking goes that 70 years of experience of injecting steam into oil and gas fields can be transferred to processes such as GeoTES — and it's hoped the switch will be financially practical." – **Guangdong Zhu**, The San Diego Union Tribune interview.

NPR
Oil industry could help the Biden administration tap 'invisible' green energy
May 8, 2024

"Geothermal is a subsurface resource, just like hydrocarbons. It requires pipes, it requires drilling, these are all skills and trades that we have in the U.S. and it's a much smoother transition to geothermal than to maybe some other technologies." – **Amanda Kolker**, NPR interview.

The Guardian
US aiming to 'crack the code' on deploying geothermal energy at scale
April 2, 2024

"Anywhere in the country, if you drill, it gets hotter and hotter with each mile you go deeper. In the western United States, that temperature increases fast. If you drill just one to two miles deep, you have temperatures hot enough for electricity. To get those temperatures in eastern states, you might need to drill miles and miles down, but you can use lower temperatures to directly heat or cool campuses, neighbourhoods and even towns." – **Koenraad Beckers**, The Guardian interview.

Climate One Podcast
Geothermal: So Hot Right Now
February 23, 2024

El Latino American
2 Estudiantes Latinos de la Universidad de Oklahoma Ganan Primer Lugar
February 22, 2024

USA Today
Can we count on renewable energy? Four ways wind, solar and water can power the US.
November 7, 2024

"Including other types of renewables brings additional benefits. For instance, both hydropower and geothermal power can offer dispatchable power to the grid, which may reduce the need for storage in areas where these resources are available. And geothermal technologies can also reduce the amount of demand on the electric grid by providing direct heating and cooling in buildings." – **Amanda Kolker**, USA Today interview.

SOCIAL MEDIA IMPACT

NREL social channels have nearly 500,000 followers across all platforms.

- **96** Geothermal posts on NREL channels in FY24
- **169,013** Impressions
- **1,939** Reactions
- **192** Shares
- **34** Comments
- **1,788** Clicks
- **5,450** Video Views

Communications

NREL.GOV ENGAGEMENTS

The first touchpoint for many members of the public, academia, industry, government, and beyond with NREL is through our website. In FY24, **www.nrel.gov/geothermal** webpages doubled engaged sessions, showing that users were spending more time on the website and were interacting beyond scrolling alone. Two-thirds of visitors to NREL.gov were new this year, while one-third were returning.

63% of users come to NREL's geothermal websites through search engines while 25% come from a direct link. The main channels driving engagement are organic searches (15,557), direct links (5,914), referrals (1,683), emails (181), and organic social (134). Updated NREL geothermal pages are planned for FY25.

FY24 Web Stats

- **16,346** active users
- **24,960** total sessions
- **39,312** views
- **14,761** engaged sessions*
  5,825 more engaged sessions than FY23
  62% engagement rate (compared to 35% in FY23)
- **0:54** Average length of engagement
  0:17 increase from average length of engagement in FY23

*An engaged session is a session that lasts longer than 10 seconds, has a key event (such as completing a form or watching a video), or has at least 2 pageviews.

Website analytics reflect visits from October 1, 2023, to August 2024.

NREL.GOV NEWS STORIES

NREL.gov geothermal news stories had more than 5,700 views in FY24.

FY24 Highlighted Articles

"Geothermal Under the Midnight Sun." August 30, 2024. **https://www.nrel.gov/news/program/2024/geothermal-under-the-midnight-sun.html**

"Geothermal Collegiate Competition Winners Partner With Osage Nation To Address Energy Sovereignty." June 10, 2024. **https://www.nrel.gov/news/program/2024/geothermal-collegiate-competition-winners-partner-with-osage-nation-to-address-energy-sovereignty.html**

"NREL Selected as Part of $1.6M in Federal Funding To Explore Potential of Geologic Hydrogen." April 30, 2024. **https://www.nrel.gov/news/program/2024/nrel-selected-as-part-of-16m-in-federal-funding-to-explore-potential-of-geologic-hydrogen.html**

"Leap Into New Capabilities: REopt Offers Enhanced Energy Solutions." February 29, 2024. **https://www.nrel.gov/news/program/2024/reopt-web-tool-offers-enhanced-energy-solutions.html**

"New Analysis Highlights Geothermal Heat Pumps as Key Opportunity in Switch to Clean Energy." January 26, 2024. **https://www.nrel.gov/news/program/2024/new-analysis-highlights-geothermal-heat-pumps-as-key-opportunity-in-switch-to-clean-energy.html**

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Trainor-Guitton, Whitney, Drew Siler, and Bridget Ayling. 2023. "Temperature uncertainty modelling with proxy structural data as geostatistical constraints for well siting: an example applied to Granite Springs Valley, NV, USA." *Geoenergy.* NREL/JA-5700-90346. **https://doi.org/10.1144/geoenergy2023-010.**

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Davalos-Elizondo, Estefanny, Nicole Taverna, Abra Gold, Karthik Menon, and Whitney Trainor-Guitton. 2024. Geothermal Play Fairway Analysis of Low-Temperature Resources for Sedimentary Basin Geothermal Play Types: An Example in the Denver Basin. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-91108. **https://www.nrel.gov/docs/fy24osti/91108.pdf.**

Ho, Jonathan L. and Yunzhi Chen. 2024. Identifying Regions Favorable for Geothermal Heating and Cooling Storage. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-90201. **https://www.nrel.gov/docs/fy24osti/90201.pdf.**

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Praprost, Marlena, Amy Allen, Andrew Parker, and Matthew Leach. 2024. *End-Use Savings Shapes Measure Documentation: Console Water-to-Air Geothermal Heat Pump*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-89132. **https://www.nrel.gov/docs/fy24osti/89132.pdf.**

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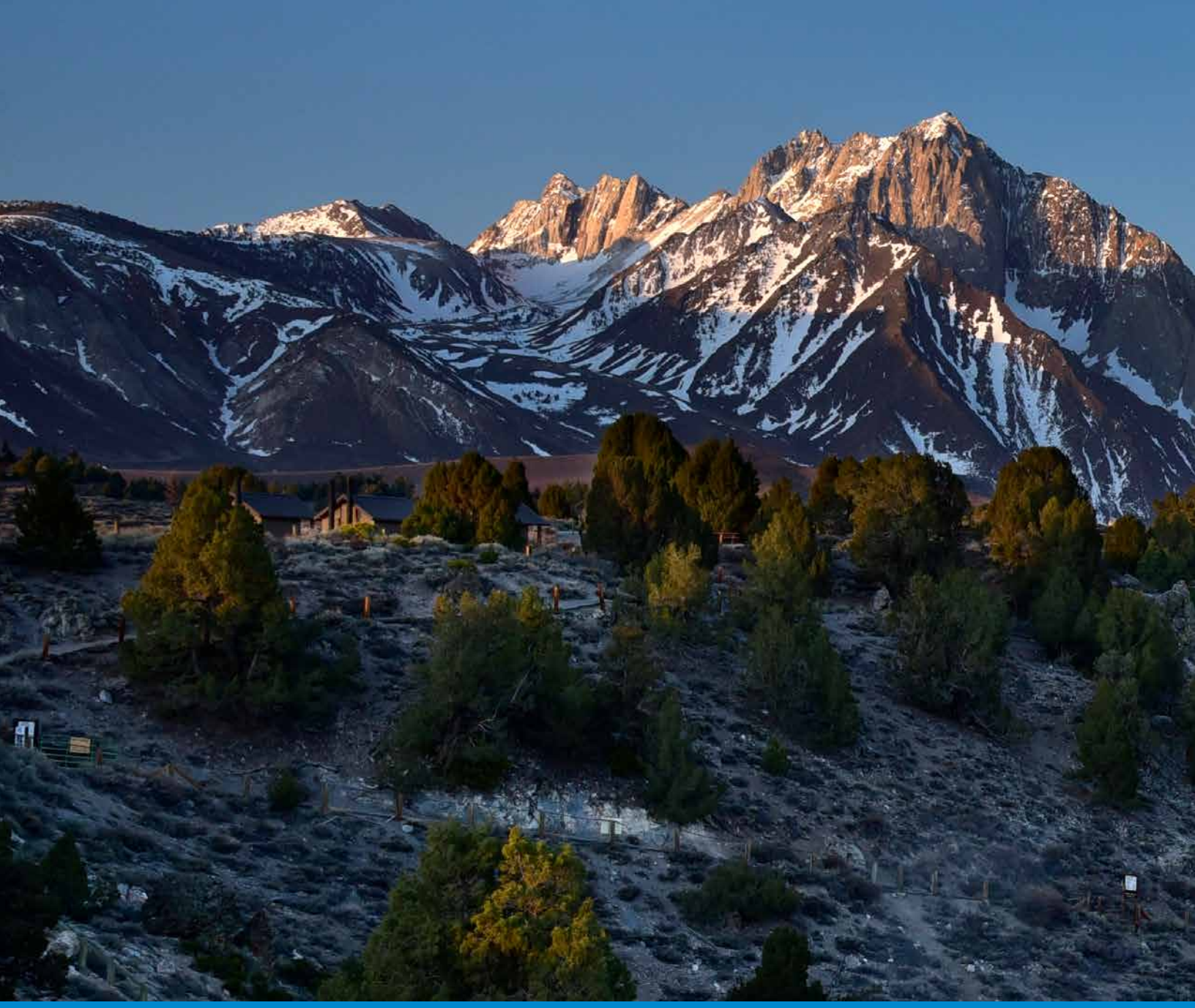

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