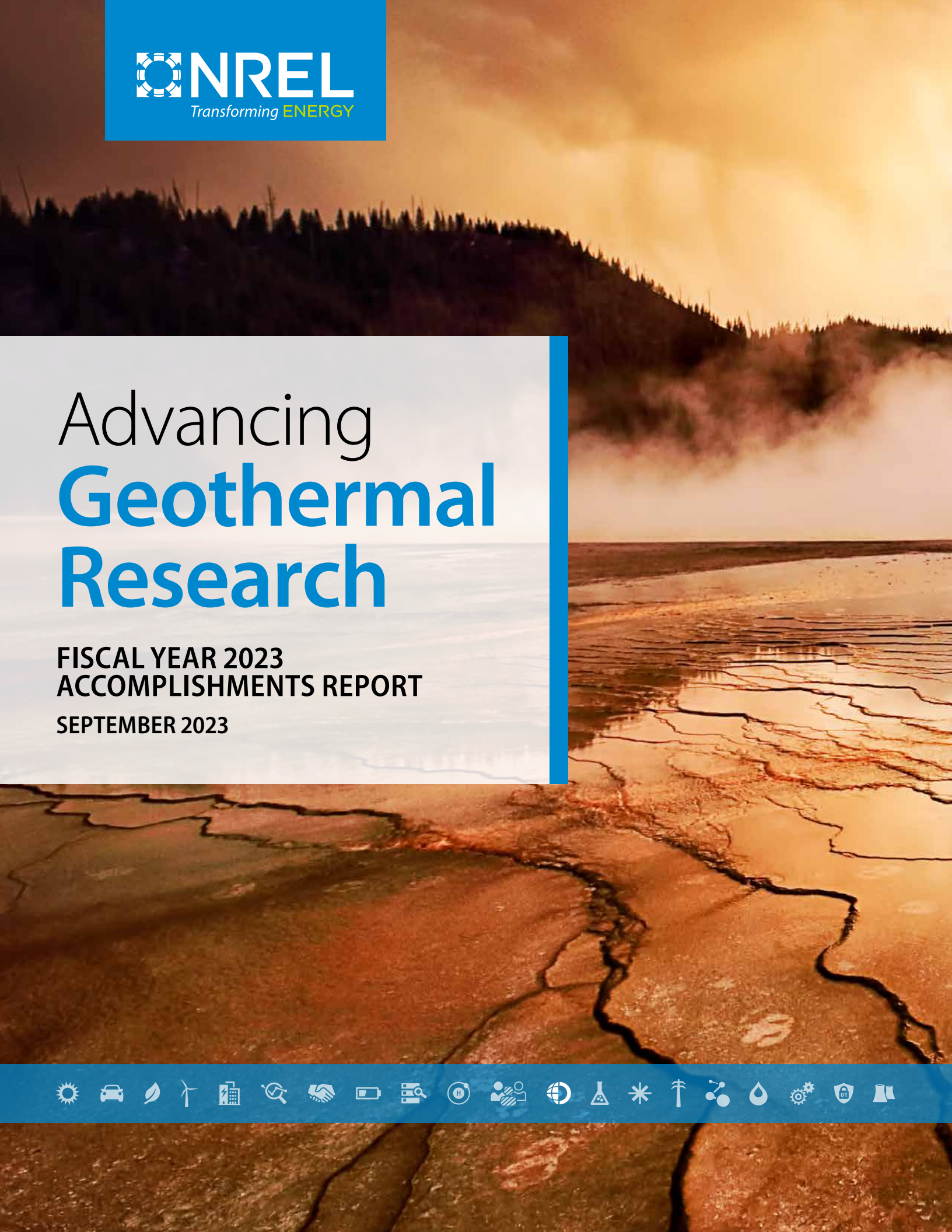

NREL
Transforming ENERGY

Advancing Geothermal Research

FISCAL YEAR 2023 ACCOMPLISHMENTS REPORT

SEPTEMBER 2023

EXECUTIVE SUMMARY

Geothermal energy has delivered renewable power for more than 100 years, and renewable heat for far longer, but recent research and advancements have shown that the potential of geothermal is largely untapped. With the ability to provide 24/7 renewable electricity, heating/cooling, and storage—plus the potential to access critical minerals and more—the Earth's subsurface is a powerhouse ready to be tapped.

Investors and leaders across both the public and private sectors are recognizing the unique value of geothermal, and the National Renewable Energy Laboratory (NREL) is leading the way by supporting the U.S. Department of Energy (DOE) Geothermal Technologies Office (GTO) in advancing geothermal energy options today and strategically planning for tomorrow.

In support of this objective during fiscal year 2023 (FY23), NREL expanded its collaborations with public and private partners, led impactful research in key technology and energy system areas, demonstrated leadership in the sector, and increased stakeholder engagement and outreach efforts.

Grand Prismatic Spring at Yellowstone National Park in the Midway Geyser Basin. *Front and back cover photo from Getty Images 1177092742; above photo from Getty Images 899846654*

Advancing Geothermal Research
2023 Accomplishments Report

RESEARCH AND DEVELOPMENT

NREL has brought the expertise of its researchers to several projects and programs that further GTO's mission and vision for geothermal energy. This includes projects like the Enhanced Geothermal Earthshot Analysis, Geothermal Operational Optimization with Machine Learning (GOOML), INnovative Geothermal Exploration through Novel Investigations Of Undiscovered Systems (INGENIOUS), Wells of Opportunity, various geothermal competitions and prizes, and many others. NREL also incorporated geothermal into NREL-developed building stock platforms and ensured geothermal representation in various NREL tools.

LABORATORY INVESTMENT IN GEOTHERMAL TECHNOLOGIES RESEARCH CAPACITIES

NREL made critical investments to expand promising research areas through the Intelligent Campus program in FY23.

INDUSTRY LEADERSHIP

NREL continued to play a pivotal leadership role in advancing GTO-specific objectives by participating in high-profile initiatives such as the development of DOE's Enhanced Geothermal Shot™, Colorado Gov. Jared Polis' The Heat Beneath Our Feet, the U.S. Iceland Clean Energy Summit, the Stanford Geothermal Conference, and other initiatives.

STRATEGIC PARTNERSHIPS

NREL research partners included national laboratories, universities, federal agencies, state and local entities, and small and large companies at the vanguard of the industry. NREL further leveraged GTO funding with strategic partners through the following initiatives: GEOTHERMICA, Federal Geothermal Partnerships, Non-Technical Barriers in Geothermal Development in California and Nevada, the Geothermal Interagency Task Force, and the Techno-Economic Analysis and Market Potential of Reservoir Thermal Energy Storage Charged with Solar Thermal and Heat Pumps.

EXPANDED STAKEHOLDER ENGAGEMENT AND OUTREACH

NREL researchers published 27 technical reports, conference papers, journal articles, presentations, posters and fact sheets, and expanded reach via www.nrel.gov/geothermal, industry conferences, and social media.

FY23 NATIONAL LABORATORY PARTNERS

Lawrence Berkeley National Laboratory

Oak Ridge National Laboratory

Pacific Northwest National Laboratory

Idaho National Laboratory

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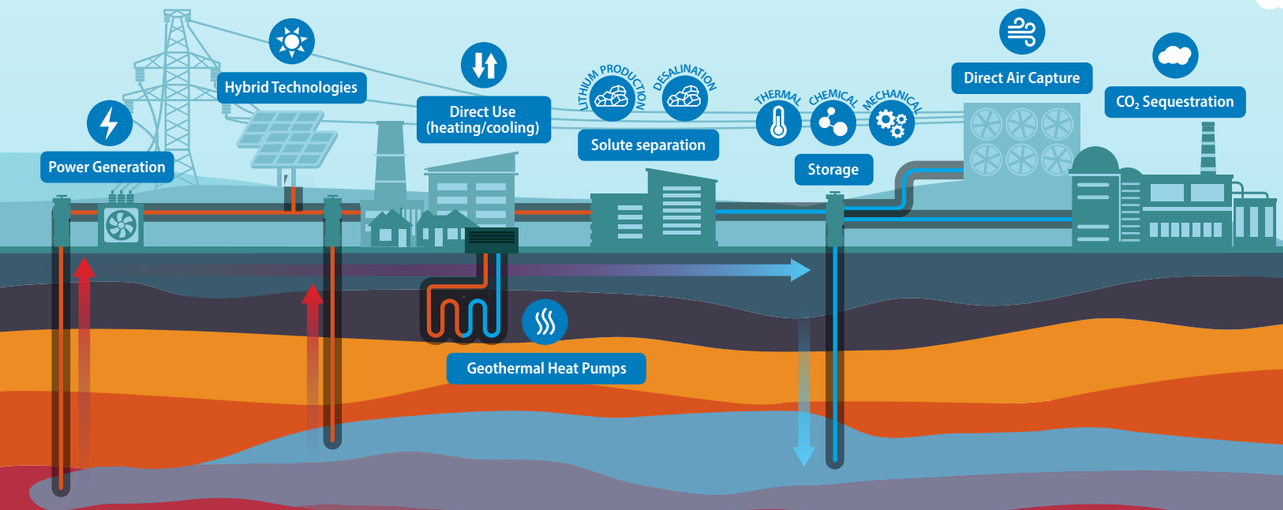
Geothermal Energy's **FULL POTENTIAL**



Geothermal energy has the potential to assist with many aspects of the transition to a clean energy economy, including energy storage, mineral extraction, and more. *Graphic by Joelynn Schroeder, NREL*

NREL GEOTHERMAL RESEARCH PROGRAM OVERVIEW & DEVELOPMENT HIGHLIGHTS

Demonstration of NREL's immersive modeling capabilities. *Photo by John De La Rosa, NREL 33631*

Advancing Geothermal Research
2023 Accomplishments Report

NREL'S GEOTHERMAL RESEARCH PROGRAM HAS THREE PILLARS: (1) TECHNOLOGIES, (2) MARKET ACCELERATION, AND (3) GRID INTEGRATION.

TECHNOLOGIES RESEARCH PILLAR

NREL's expertise in subsurface modeling, development of geothermal resources, site operations and optimization, energy analysis, techno-economic modeling, data management, and communications contributes to the advancement and commercial-scale deployment of geothermal technologies. These technologies include geothermal power generation, direct use, geothermal heat pumps, storage, and hybrid technologies. The illustration in the table of contents captures the 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, 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 reducing regulatory timeframes, 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 in the areas of cybersecurity, flexible generation, storage, and additional grid services.

RESEARCH & DEVELOPMENT HIGHLIGHTS:
TECHNOLOGIES RESEARCH PILLAR

NREL ENHANCED GEOTHERMAL SHOT ANALYSIS SUPPORTS DOE'S ENERGY EARTHSHOTS INITIATIVE

Significantly expanding enhanced geothermal system deployment by 2035 is ambitious but achievable with recent technological advances.

As part of DOE's ongoing Energy Earthshots initiative, NREL conducted and published an analysis supporting DOE-GTO's Enhanced Geothermal Shot™ goals and targets. The results concluded that significantly expanding enhanced geothermal system (EGS) deployment by 2035 is ambitious but achievable with recent technological advances.

Building on the 2019 GeoVision report, the 2023 analysis by NREL researchers Chad Augustine, Erik Witter, Sarah Fisher, and Jonathan Ho utilizes updated modeling assumptions and estimates of EGS resource potential to show that by 2050 the total amount of installed domestic geothermal capacity could reach 90 gigawatts-electric—nearly 25 times the current installed capacity.

To identify aggressive but technically achievable cost reductions, NREL researchers modeled scenarios harnessing technology improvement that would lower costs related to drilling, cement, well casing, and other materials and equipment. They also optimized development and production technologies and timelines, and developed an improved baseline dataset for the available EGS resource base by integrating new and regional subsurface data and models. These analyses helped inform an Earthshot target of EGS cost reduction by 90% by 2035.

In addition to lowering costs, the analysis expands the footprint of future EGS development on the map. Traditionally, geothermal electricity generation has been limited to western regions in the U.S. that have the necessary water, heat, and permeability. However, EGS has the potential to be developed anywhere in the country to increase clean heating and cooling solutions for millions of Americans. This report concludes that by 2035, geothermal deployment could extend further east, with particular opportunities in the Appalachian Basin. By 2050, the expansion could encompass most of the Gulf Coast region (see map below).

The Enhanced Geothermal Shot Analysis defines the possibilities that EGS presents and will aid in deployment of this energy source to help meet DOE's goal of reaching 100% decarbonization by 2050.

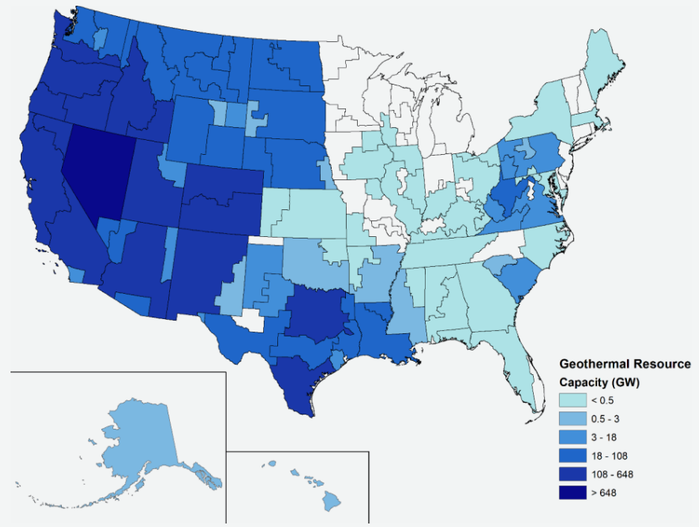
View the full report here: https://www.nrel.gov/docs/fy23osti/84822.pdf.

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Enhanced Geothermal™

Impact: Updated modeling and estimates of EGS resource potential show that by 2050 the total amount of installed domestic geothermal capacity could reach 90 gigawatts-electric—nearly 25 times the current amount generated.

Enhanced Geothermal Shot Technology Assumptions Compared to Baseline Values

GETEM Input		Business as Usual	Enhanced Geothermal Shot™
RESOURCE EXPLORATION	*Exploration — Pre-Drilling Costs ($/project)*	$250K	Same as BAU
	Exploration — Drilling Costs ($/project)	$1.5M–$5M	2/3 of BAU
	Full-Sized Confirmation Well Costs	Base + 50%	Ideal + 0% (no premium)
	Full-Sized Confirmation Well Success Rate	50%	75%
	Number of Full-Sized Confirmation Wells Required	9	3
DRILLING	*Drilling Success Rate*	75%	90%
	Drilling Costs	Base	80% of Ideal drilling costs from *GeoVision* study
RESERVOIR CREATION	*Well Flow Rate* (flow rate per production well)	40 kg/s	125 kg/s
	Well Productivity	0.46 kg/s/bar	Production: 38.1 kg/s/bar Injection: 70 kg/s/bar
POWER PLANT	*Plant Size*	25 MW_e	100 MW_e



Total U.S. geothermal resource capacity (GWe) by ReEDS balancing authority used for the Earthshot analysis. Resource capacity map includes estimates for Hawaii and Alaska. *Graphic by NREL.*

GEOTHERMAL POWER PLANT OPTIMIZATION OPPORTUNITIES EXPLORED THROUGH COLLABORATIVE GOOML PROJECT

The digital platform allows geothermal power plant operators to improve the efficiency of geothermal steam fields through the analysis of historical operational data and the application of custom machine learning algorithms.

In FY23, the Geothermal Operational Optimization with Machine Learning (GOOML) project completed a digital platform that allows geothermal power plant operators to improve the efficiency of geothermal steam fields through the analysis of historical operational data and the application of custom machine learning algorithms.

GOOML brings together industry specialists from the United States and New Zealand on a GTO initiative to optimize geothermal operations through machine learning. This project was tested with data from three different operating geothermal fields: Ormat's McGinness Hills Geothermal Power Plant in Nevada; NTGA's Kawerau Geothermal Power Plant in New Zealand; and Contact Energy's Wairakei Geothermal Power Plant in New Zealand.

Utilizing the geothermal, machine learning, and data analytics expertise of NREL's researchers, GOOML takes real-world geothermal problems and codifies them into a digital framework that allows users to explore data-driven solutions. This includes predicting future operational scenarios, such as well shuts-ins, workovers, maintenance outages, and steam field expansion.

Validated on three different steam fields with multiple data streams and unique configurations, GOOML provides a universal foundation on which to build and run a variety of experiments that train its own predictive models utilizing real-world geothermal operational datasets. This component-based systems model is inspired by state-of-the-art thermal-hydraulics software, but with the integration of machine learning-based component performance models. This provides a framework to perform advanced experimentation, such as reinforcement learning and the application of genetic algorithms that can optimize steam field physical parameters.

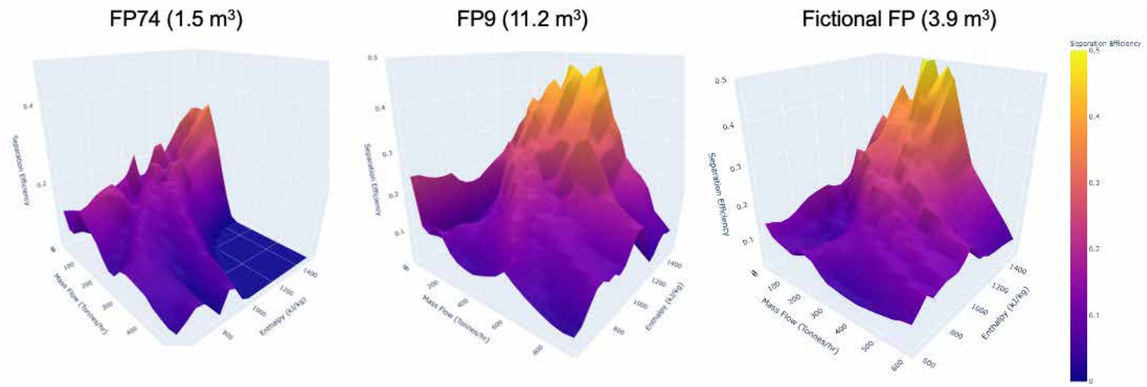
Exploring these configurations through traditional methods would require months of staff labor, whereas GOOML can run experiments in hours. GOOML's data curation algorithms analyze thousands of data points to assist users with data input for model training, minimizing input errors, and allowing for steam field operators to make decisions supported by data and analysis. GOOML identifies optimal configurations to allow power plants to produce more energy from existing resources, potentially lowering the cost of geothermal energy while increasing the capacity factors of geothermal plants.

This system can also be used to increase the availability of geothermal energy through life cycle analysis and the optimization of steam field production over time. Widespread adoption of GOOML would also showcase the benefits of using digital twins and advanced data analytics for the geothermal industry and promote adoption of geothermal technologies.

NREL researchers who contributed to GOOML include Jon Weers, Grant Buster, Nicole Taverna, Michael Rossol, and Jay Huggins. An NREL technical report on GOOML is available at: https://www.nrel.gov/docs/fy22osti/81649.pdf.

Partners: Ormat Technologies Inc., Upflow Limited, Contact Energy Limited, and Ngāti Tūwharetoa Geothermal Assets (NTGA) Limited.

Impact: On average, GOOML showed a potential to improve availability factors of existing geothermal plants by 2-10%.



Flash plant prediction surfaces. *Figure by Grant Buster, NREL*

Wairakei Steam Field, part of the GOOML Project, with two-phase and dry steam wells, flash, and binary units. *Photo from Contact Energy*

INGENIOUS AIMS TO DISCOVER HIDDEN GEOTHERMAL SYSTEMS

NREL is providing geostatistical 3D modeling expertise to the INnovative Geothermal Exploration through Novel Investigations Of Undiscovered Systems (INGENIOUS) project, which creates risk reduction methodologies for geothermal power plant exploration.

Hidden geothermal resources cannot be identified from surface expressions, so industry must rely on combined geophysical methods, qualitative geologic models, and sparse drilling information about depth to make assessments—leading to non-uniqueness and low levels of confidence. This project is the first of its kind to fully integrate play fairway analysis, 3D and conceptual modeling, and resource capacity estimation to reduce uncertainty in prospecting for hidden systems.

NREL researcher Whitney Trainor-Guitton is leading the NREL team providing 3D geostatistical modeling expertise and value of information analysis to de-risk well placement. Stochastic co-simulation methods were applied for the first time in a geothermal application. These methods blend the 3D spatial correlation of temperatures and secondary geologic data (e.g., dilation tendency, proximity to faults) to generate many possible 3D temperature models, which are used to assess the variability or uncertainty of temperature in the subsurface. Locations favorable for high temperatures at depth, and locations with high uncertainty, were both targeted to find the economic potential and eliminate certain conceptual models, respectively. These results were presented at the 2023 Stanford Geothermal Workshop.

Initial efforts focused on Nevada, and the project has now expanded its study area to the broader Great Basin region (including southern Idaho, California, and western Utah) for early-stage prospect identification. Covering such a diverse area requires a large team of expert collaborators from national laboratories, industry, and federal and state agencies.

The framework for INGENIOUS draws from oil and gas industry methods, while developing new approaches to gather sufficient data to understand the geothermal potential of a site. This includes working with impacted communities to appropriately address uncertainties surrounding geothermal power plant development.

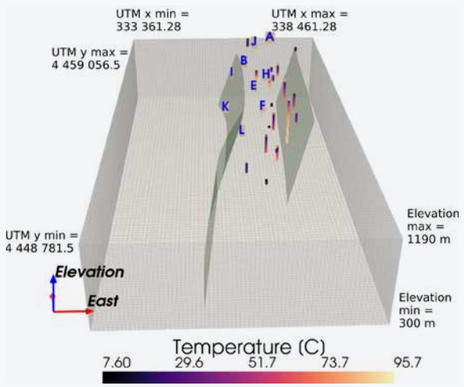
New prospects for geothermal exploration have already been identified through this project, and the advanced methodologies will result in best practices for developers to find the areas with the most geothermal potential.

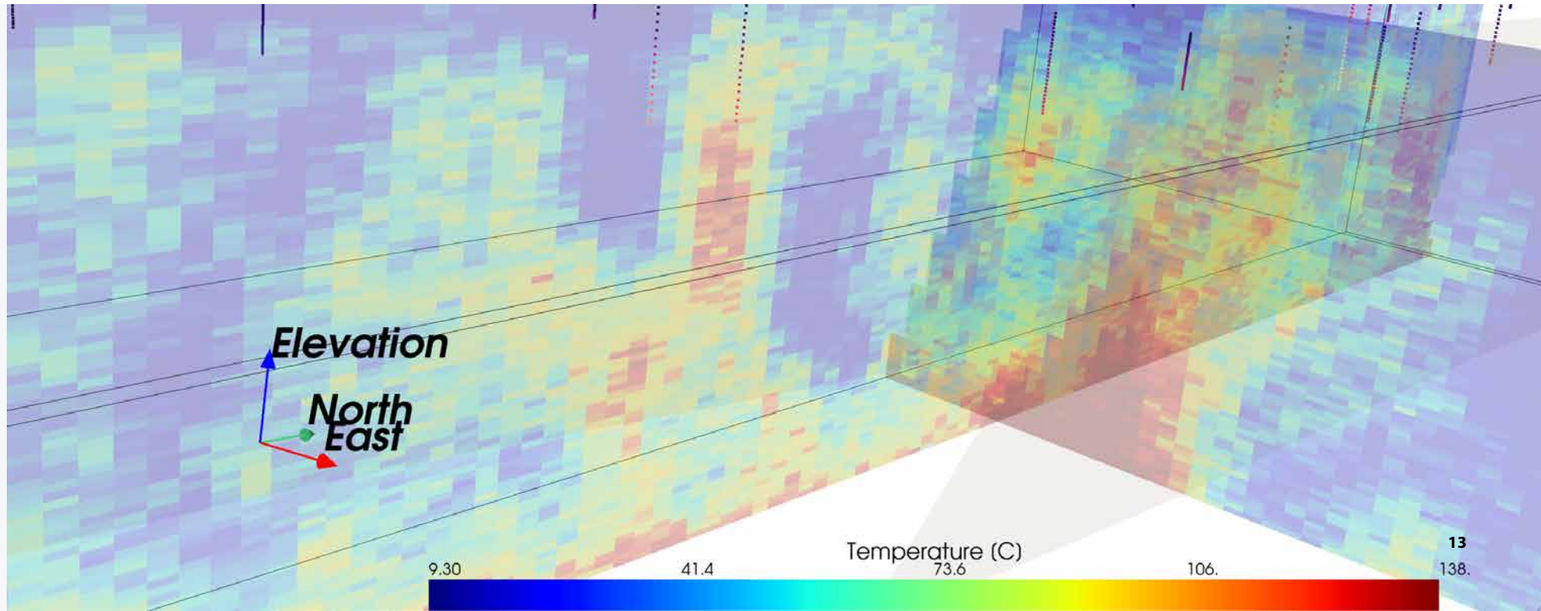
Partners: **United States Geological Survey, Utah Geological Survey, Idaho Geological Survey, Lawrence Berkeley National Laboratory, Rasse Power Systems, Geothermal Resources Group, Hi-Q Geophysical, Aprovechar Lab L3C, Petrolern Ltd., and Innovate Geothermal Ltd.**

Impact: **Reduces risk for geothermal power plant exploration and development, which is a major barrier for geothermal technology uptake.**

LEFT: Geostatistical modeling volume with two faults (shaded) from the Granite Springs Valley conceptual model, the temperature data projected onto well traces, and the nine candidate well locations labeled with blue letters at the surface. *Figure by Whitney Trainor Guitton, NREL*

RIGHT: Subsurface view of two perpendicular cross sections (opaque panels) from a 3D temperature model. Existing wells displayed as vertical solid lines. *Figure by Whitney Trainor Guitton, NREL*





REPURPOSING OIL AND GAS WELLS FOR GEOTHERMAL ENERGY THROUGH WELLS OF OPPORTUNITY

The initiative explores the feasibility of utilizing existing oil and gas wells for geothermal energy.

NREL researchers are involved in two projects awarded under GTO's Wells of Opportunity (WOO) initiative, which explores the feasibility of utilizing existing oil and gas wells for geothermal energy. With few examples of active oil and gas wells being repurposed this way, the two WOO projects—WOO Nevada and WOO Oklahoma—will showcase effective, cost-saving decarbonization measures that owners of oil and gas wells can implement.

GENERATING GEOTHERMAL ELECTRICITY FROM A NEVADA OILFIELD

At the Blackburn Oilfield in Nevada, several active oil wells are producing fluids with a hot water cut of 99%. Historically, this water has been reinjected at the site without utilizing this heat and at a liability to operators. Colorado-based Transitional Energy, Grant Canyon Oil and Gas, Electratherm, and NREL are partnering to recover the wasted hot water and turn it into an opportunity for power generation. The team will install state-of-the-art modular organic Rankine cycle units to instead produce clean electrical power from the geothermal heat.

NREL researchers, including PI Koenraad Beckers, Kagan Kutun, and Abra Gold, are providing technical support by modeling the reservoir heat and fluid flow, and performing techno-economic simulations of the surface installation. These simulations will project how this system will perform decades after installation, providing an operational strategy that will ensure a 30-year lifetime for hot water production.

If successful, WOO Nevada will showcase repurposing oil and gas wells to generate electricity with geothermal technologies. Documentation associated with the project will act as an open-source blueprint, which researchers hope will encourage other companies to easily replicate their work at their own sites.

Partners: Transitional Energy, Grant Canyon Oil and Gas, Electratherm

Impact: This proof-of-concept project will support the implementation of geothermal energy production in existing oil fields, accelerating the energy transition and helping decarbonize the oil and gas industry.

"RECYCLING" OIL WELLS IN OKLAHOMA FOR GEOTHERMAL HEATING AND COOLING

In Tuttle, Oklahoma, NREL is partnering with the University of Oklahoma and Blue Cedar LLC to "recycle" four existing oil and gas wells to produce up to 10 MWth of geothermal energy for direct-use applications. WOO Oklahoma is setting its sights on serving heating and cooling demand in Tuttle Elementary and Tuttle Middle schools, as well as 250 nearby houses. These users are only a mile away from the targeted wells, which have sufficient depth to tap ~90°C geothermal fluids from around 3 KM below the ground surface.

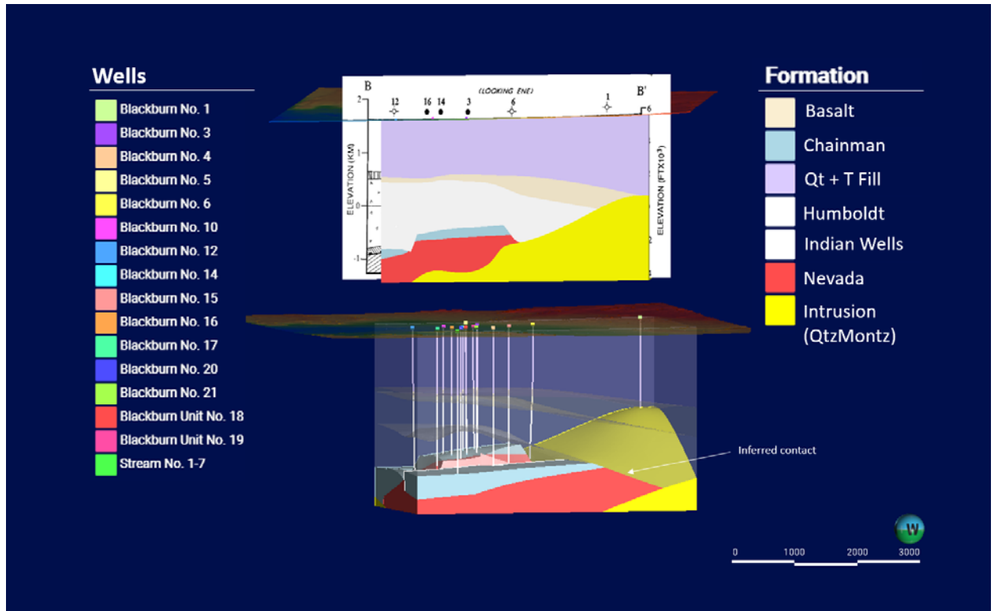
This ground-breaking initiative requires the successful development and execution of a field test, which will determine whether these oil and gas wells in Oklahoma can be repurposed for geothermal energy heating and cooling for the nearby community. It will also incorporate a smart well completion system that utilizes downhole sensors and surface-controlled downhole flow control valves, enabling monitoring, evaluating, and actively managing injection in real time without any well interventions.

To achieve this, NREL PI Hyunjun Oh will spend two years undertaking a holistic analytical approach: characterizing the subsurface (formation, thermal gradient, and geochemistry); performing techno-economic analysis; and conducting life cycle greenhouse gas emissions and electrical grid impact analyses. Other NREL researchers involved with WOO Oklahoma in FY23 include Sertac Akar, Eric Bonnema, Koenraad Beckers, and Estefanny Davalos Elizondo.

Ultimately, the team behind WOO Oklahoma intends to expand geothermal energy in oil and gas "hot spots" while reducing the cost and risk associated with drilling wells. Utilizing existing wells allows oil and gas companies to decarbonize and unlocks new potential for implementation in underserved communities.

Partners: The University of Oklahoma and Blue Cedar LLC

Impact: This project demonstrates possibilities associated with recycling existing oil and gas wells, promoting adoption of geothermal technologies by well owners to benefit local communities and other geothermal energy off-takers.



Preliminary geologic model of the Blackburn Field, NV.

GEOTHERMICA COLLABORATIONS

GEOTHERMICA PROJECTS SUPPORT MULTINATIONAL GEOTHERMAL COLLABORATION OPPORTUNITIES FOR NREL RESEARCHERS

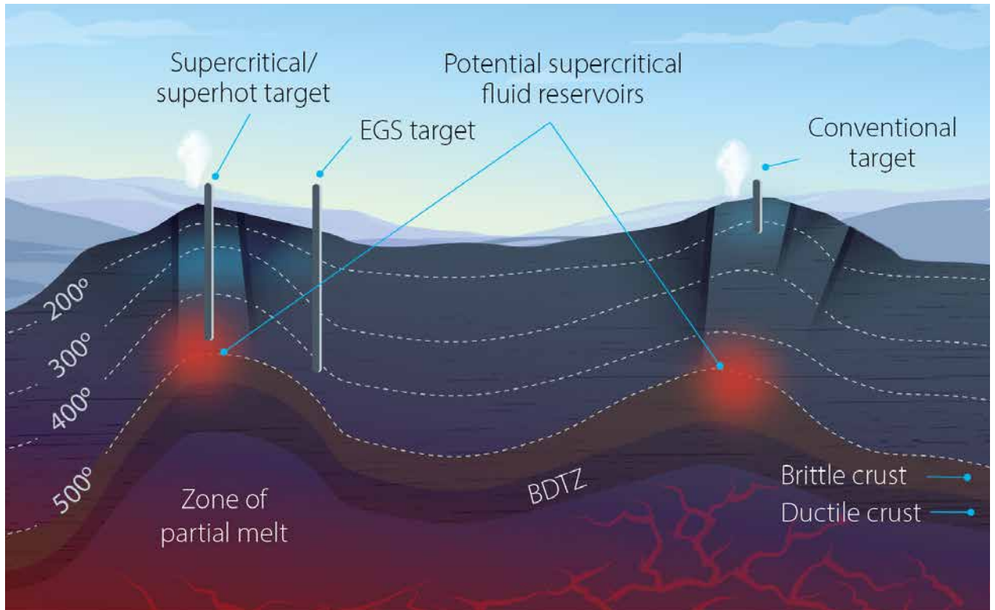
The GEOTHERMICA transnational consortium is a collaborative initiative that aims to accelerate the deployment of geothermal energy globally, encouraging research and innovation to improve business cases for geothermal energy across Europe, the United States, and the Middle East. DOE joined the GEOTHERMICA consortium in 2021 as the participating U.S. funding agency, and NREL is part of three projects through the support of GTO: DEEPEN, FLXenabler, and the CHANGE. Each research project is funded for a three-year duration.

Impact: Fostering collaboration between international and U.S. geothermal experts to spark innovation.

DEEPEN
2021-2024

The DEEPEN project (DErisking Exploration for geothermal Plays in magmatic ENvironments), led by NREL researcher Amanda Kolker, aims to better understand a new type of resource—supercritical or superhot geothermal—through observations and modeling. In addition to characterizing the resource potential of these ultrahot systems, the project is developing techniques and workflows to find the deep and superhot resources. The project is a multinational collaboration among several universities, institutes, and energy companies.

Partners: Equinor, Reykjavik Energy, ISOR, NORSAR, Lawrence Berkeley National Laboratory, and other international research institutions



Conceptual model of several geothermal "plays" (i.e., resource targets) in the same subsurface magmatic environment. Dotted lines represent hypothetical temperature isotherms. *Figure by Joelynn Schroeder, NREL*

FLXENABLER
2023-2026

FLXenabler (Flexible Heating and Cooling and Geothermal Energy Storage as an Enabler for Decarbonized Integrated Energy Systems) seeks to evaluate the flexibility that geothermal heating, cooling, and storage can bring to decarbonized integrated energy systems. This project, led by NREL researcher Whitney Trainor-Guitton, investigates 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 will provide electric power modeling and subsurface geothermal district energy techno-economic analysis expertise to the project. Looking at different case studies in Europe and the United States, the project will suggest possible future business cases for energy community implementation.

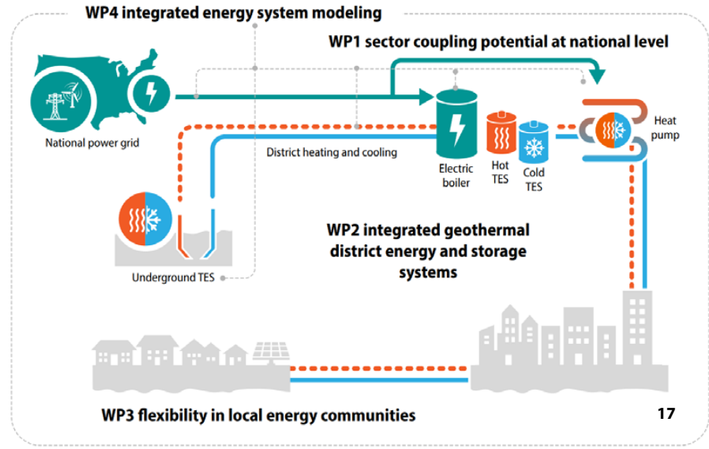
Partners: United States Geological Survey, SINTEF, Equinor, TU Wien

THE CHANGE
2023-2026

Led by NREL researcher Matt Mitchell, the CHANGE (The Cooling and Heating transition Acceleration via Network Geothermal Energy) develops design and screening tools for geothermal district energy systems, which supports heating and cooling decarbonization through the deployment of climate-neutral shallow geothermal energy resources. In addition to supporting decarbonization, this project fosters international and internal collaboration between geothermal and buildings researchers. NREL will develop models to enable fast design and simulation of district-connected ground-source heat pumps. Utilizing advanced software and simulation development expertise, NREL will play a key role in developing the overarching simulation platform and approaches, ensuring that all pieces are seamlessly integrated.

Partners: Oak Ridge National Laboratory, Oklahoma State University, Lund University, Swedish GeoEnergy Center, VIA University, Danish Geologic Survey, GeoDrilling, Skanska

FLXenabler project concept. The project has four scientific work packages (WPs): WP1 focuses on mapping the flexibility potential from sector coupling at the national level, WP2 develops flexible geothermal district energy systems and studies their impact at a national scale, while WP3 focuses on enabling flexibility at a community level. WP4 performs integrated energy system modeling to quantify how coupling of heating, cooling, and electricity sectors at these three levels can accelerate and reduce the costs of the ongoing transition to a fully decarbonized energy system in Europe and the U.S. *Figure by SINTEF*



NREL-LED TEAM EXPLORING UNDERGROUND THERMAL ENERGY STORAGE FOR ALL SEASONS

A new project led by NREL aims to address the increasing need for renewable energy storage technologies with long-duration capabilities by evaluating the feasibility of seasonal energy storage in underground reservoirs. By storing excess energy as thermal energy underground, energy generated at one point in time can be captured, stored, and recovered for use after many months or even seasons. Stored thermal energy has the potential to generate electricity and directly produce heat that can be used by buildings or industrial processes. The energy can also be kept in cold storage reservoirs to be used for building and industrial cooling.

NREL researchers Guangdong Zhu, Dayo Akindipe, Josh McTigue, and Erik Witter are exploring these cutting-edge concepts as part of the "Techno-Economic Analysis and Market Potential of Reservoir Thermal Energy Storage Charged with Solar Thermal and Heat Pumps" project. This collaboration also includes Lawrence Berkeley National Laboratory, Idaho National Laboratory, Premier Resource Management, and Earthbridge Energy.

The national laboratories will develop two case studies to validate this concept. The first, in partnership with Premier Resource Management, explores the use of underground reservoirs in legacy oil and gas fields in California, hybridized with solar thermal technologies. Despite previous successful implementation of thermal energy storage in shallow aquifers in the United States and western Europe, there are currently no commercial thermal storage projects in reservoirs associated with depleted oil and gas fields. Successfully utilizing depleted oil and gas fields to store excess renewable energy will not only generate value from stranded assets and address grid stability issues, but it should also encourage oil and gas industries to participate in the transition to a decarbonized energy economy.

The second case study, in partnership with Earthbridge Energy, will explore the application of high-efficiency heat pump technologies to store excess wind power into water reservoirs in Texas. When subsurface thermal energy storage technologies are hybridized with heat pump technologies, it also may provide significant cost savings to communities faced with high heating and cooling bills by mitigating the excess electricity generation of non-flexible renewables (i.e. photovoltaics and wind) through low-cost underground storage. Demonstrating the economic possibilities of these systems could accelerate deployment, allowing a diverse range of consumers and communities to benefit.

Partners: **Lawrence Berkeley National Laboratory, Idaho National Laboratory, Premier Resource Management, and Earthbridge Energy.**

Impact: **Using the Earth's subsurface for long-term energy storage will facilitate deployment of renewable power and heating and cooling technologies.**

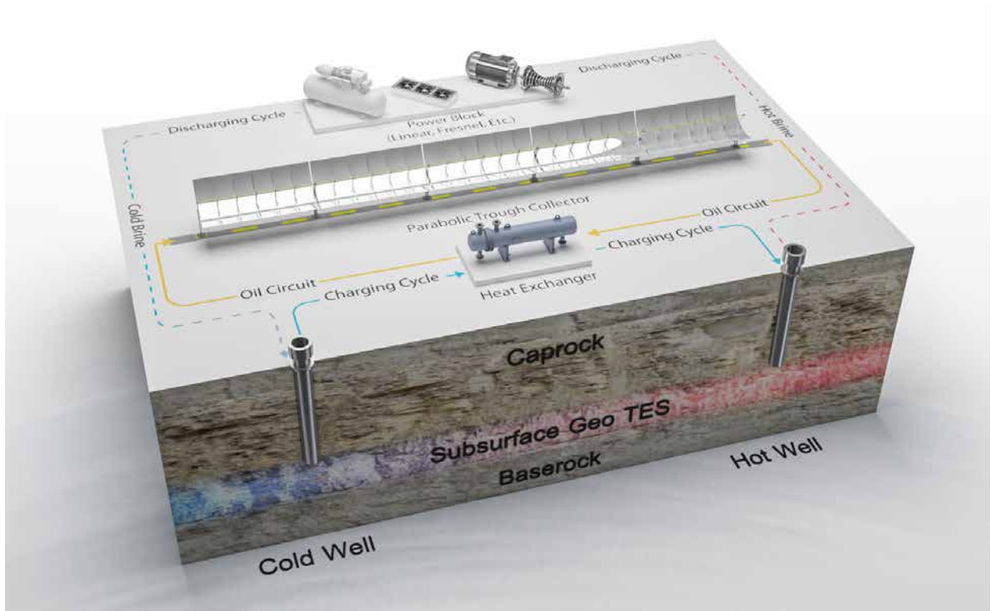


Illustration of one kind of underground thermal energy storage technology using geological thermal energy storage (GeoTES).
Figure by Josh Bauer, NREL

Photo by Dennis Schroeder, NREL 46219

NREL DISTILLS BEST PRACTICES FOR GEOTHERMAL PFA FROM A RETROSPECTIVE ANALYSIS

A team of NREL researchers—Hannah Pauling, Nicole Taverna, Whitney Trainor-Guitton, Erik Witter, and Amanda Kolker—along with a number of external collaborators, finalized a retrospective analysis of the DOE-GTO geothermal play fairway analysis (PFA) program. As the final step, the team published a report that details PFA best practices.

PFA methodology aims to improve success rates for geothermal exploration by identifying hidden hydrothermal systems. The methodology involves systematically screening a given region for features associated with the presence of hidden subsurface resources. Over the past decade, GTO supported 11 research teams across the country to adapt and apply this methodology. Those teams produced a wealth of valuable data and outputs, including regional-scale geothermal favorability maps.

The NREL Retrospective Analysis evaluated and synthesized outcomes from those 11 projects to find common approaches and distill best practices for geothermal PFA. The study found that the program was successful in three ways: first, it resulted in extensive new data and discoveries of unrecognized geothermal systems; second, it advanced the state-of-the-art for geothermal exploration techniques and analytical methods; and third, it identified systematic gaps in data collection and drilling practices that, if addressed by the larger geothermal community, would help advance and de-risk geothermal exploration.

Impact: Sharing PFA best practices with the geothermal community provides much needed guidance for future exploration of advanced geothermal approaches.

Locations of GTO's PFA projects.
Photo courtesy of GTO.

Advancing Geothermal Research
2023 Accomplishments Report

ISLAND HEAT LEVERAGES MACHINE LEARNING TO ASSESS GEOTHERMAL POTENTIAL ON HAWAI'I

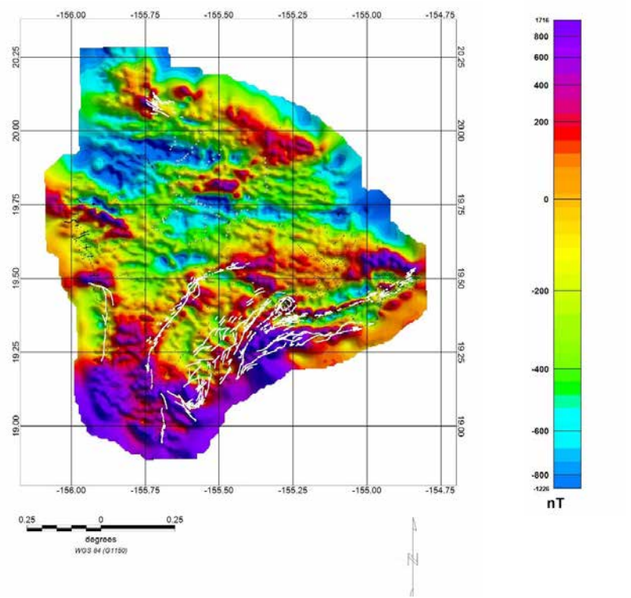
Hawai'i is an ideal candidate for expansion of geothermal power production, with high power prices and strong demand for reliable and flexible baseload power generation. Existing proven geothermal resources on the Big Island also increase the likelihood of further geothermal potential.

To assess geothermal potential on Hawai'i, the Innovative Subsurface Learning and Hawaiian Exploration using Advanced Tomography (ISLAND HEAT) project leveraged and enhanced diverse data sets and existing geothermal play fairway analysis results to develop conceptual models of ocean-island hydrothermal systems. These data together can be used to inform multimodal machine learning algorithms to identify and predict the numerical and categorical features associated with hidden geothermal systems, helping to define the fingerprint of prospective resources and target heat and permeability prior to drilling expensive, high risk, exploratory wells.

Partners: Hawai'i Groundwater & Geothermal Resource Center, Hawai'i Institute of Geophysics and Planetology, University of Hawai'i-Manoa, Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, Jarpe Data Solutions

Impact: Diverse data sets were compiled and processed to predict geologic characteristics and geophysical signatures of ocean-island hydrothermal systems, while an evolving conceptual model provides the context for understanding the components of hydrothermal systems occurring in active, historic, and extinct Hawaiian volcanic rifts.

Map of total magnetic field intensity on the Hawai'i Island. White lines indicate mapped faults. Red and purple colors show regions with high magnetic susceptibility.



RESEARCH & DEVELOPMENT HIGHLIGHTS:
MARKET ACCELERATION RESEARCH PILLAR

OVERCOMING NON-TECHNICAL BARRIERS TO GEOTHERMAL DEPLOYMENT

In FY23, NREL released a report on Non-Technical Barriers in Geothermal Development in California and Nevada, highlighting non-technical barriers at the federal, state, and local levels that may influence geothermal project development timelines in those states.

California and Nevada are the largest producers of geothermal energy in the United States. As such, this study explored the various challenges that persist in developing geothermal resources in those states, in order to inform best practices for other states as use of geothermal resources expand. The study found that delays in project implementation due to lengthy permitting and regulatory processes is a major barrier to geothermal development in CA and NV. Specific areas of concern are: (1) duplicative permitting requirements; (2) coordination efforts between federal, state, and local authorities including agencies and tribes; and (3) overly lengthy federal and state environmental review processes. In addition, the report identified site-specific natural and culture resource complications to consider that may impact project development, such as protecting endangered species and water quality and water resources.

These delays exacerbate the risks and uncertainties related to geothermal development. They also add costs to a project in the risky early phases of geothermal development. Coupled with other risks and uncertainties related to geothermal development (notably the resource risk related to the high cost of exploration drilling), these additional—and avoidable—risks further impede market uptake of geothermal technologies.

Best practices to reduce delays include:

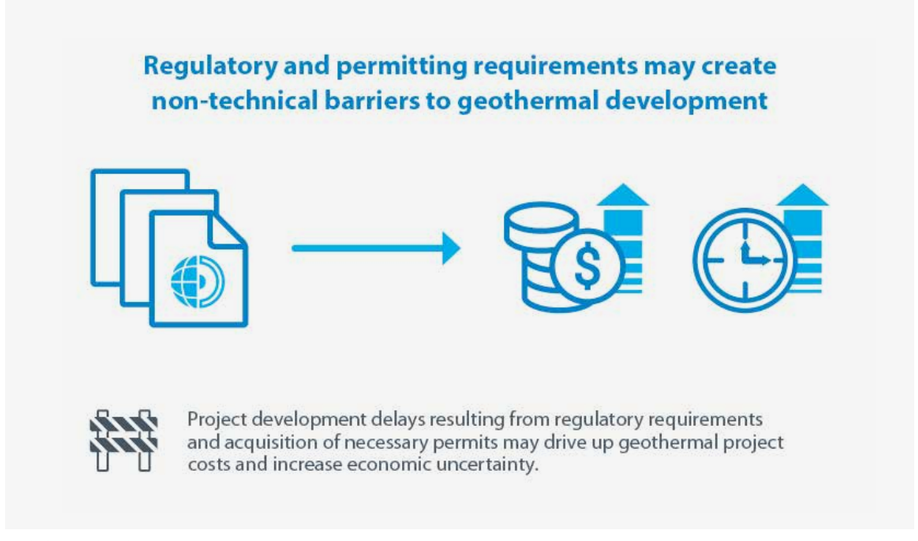
- Tiering to (i.e., building upon) existing environmental review documents, which may create cost and time efficiencies for agency staff and project developers.
- Development of interagency memoranda of understanding (MOUs), which may decrease project permitting delays through increased interagency coordination and communication.
- Development of comprehensive and agency-integrated permitting and review processes, which may decrease project development delays by reducing duplication of efforts and streamlining existing procedures.

Implementing these steps in geothermal project development may reduce overall timelines, costs, risks, and uncertainties associated with regulatory and permitting requirements.

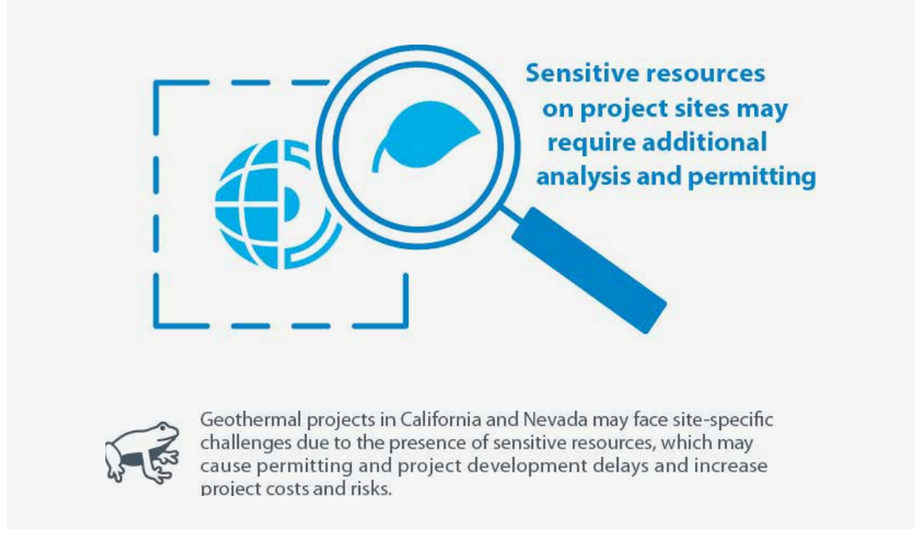
Project team members included Aaron Levine, Ligia E.P. Smith, Jody Robins, Erik Witter, Caity Smith, and Clare Haffner. The full report can be found at https://www.nrel.gov/docs/fy23osti/83133.pdf.

Partners: **Pacific Northwest National Laboratory, Idaho National Laboratory**

Impact: **Understanding non-technical barriers that impede geothermal development helps inform best practices to alleviate project costs, risks, and other uncertainties.**



Graphic by Jessie Alexander, NREL



Graphic by Jessie Alexander, NREL

GEOTHERMAL PARTNERSHIPS INITIATIVE HELPS EXPAND GEOTHERMAL HEATING AND COOLING AT FEDERAL SITES

NREL is partnering with other national labs, industry, and academia to implement geothermal heating and cooling for the nation's largest energy user: the federal government. The Federal Geothermal Partnerships (FedGeo) program provides technical assistance to stakeholders on geothermal heating and cooling systems. Not only will this help accelerate uptake of this technology at federal sites, but it will also serve to demonstrate its benefits and potential to the general public.

NREL's team consists of researchers Matt Mitchell, Hyunjun Oh, Koenraad Beckers, Dareum Nam, and Ben Park. This large consortium—led by Oak Ridge National Laboratory, with partners Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, Illinois State Geological Survey, International Ground Source Heat Pump Association, Oklahoma State University, and the University of Wisconsin-Madison—will develop an advanced technical assistance framework for the deployment of geothermal heating and cooling technologies. Those technologies include geothermal heat pumps, geothermal direct use, and hybrid technologies; specific technologies will be selected for individual sites based on site characteristics. The team will collect data through site visits and surveys, measure subsurface properties, carry out resource characterization and develop system models for estimating the size and performance of the selected technology.

The goal of the technical assistance framework is to provide federal agencies with advanced assistance on a rolling basis; initial engagement is focused on the U.S. Military Academy at West Point in New York and the U.S. Army Garrison Detroit Arsenal in Michigan. The federal government is the nation's largest energy user, so successful adoption of geothermal heating and cooling systems at federal facilities will demonstrate the benefits of these technologies while furthering national decarbonization goals.

For each site, the team will produce techno-economic analysis reports that describe the potential for deploying geothermal technologies. The reports will provide information collected on the subsurface heat exchange potential, opportunities for building upgrades and retrofits to use geothermal heating and cooling technologies, and the financial viability of the designs: https://www.energy.gov/eere/geothermal/articles/leading-way-gto-announces-federal-sites-pursue-geothermal-projects.

Partners: **Oak Ridge National Laboratory, Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, Illinois State Geological Survey, International Ground Source Heat Pump Association, Oklahoma State University, and the University of Wisconsin-Madison**

Impact: **Implementing geothermal heating and cooling at federal locations will aid in decarbonization efforts and promote adoption at additional sites.**

Cadets from the U.S. Military Academy in West Point, New York. *Photo by Tyler Williams, U.S. Army*

RESEARCH & DEVELOPMENT HIGHLIGHTS: MARKET ACCELERATION

Advancing Geothermal Research
2023 Accomplishments Report

GEOTHERMAL COMPETITIONS AND PRIZES ADMINISTERED BY NREL BOOST CLEAN ENERGY WORKFORCE

NREL is administering a number of GTO geothermal competitions and prizes, providing comprehensive strategic and logistical support, and assisting with outreach and program promotion.

Impact: Geothermal competitions and prizes promote innovation and interdisciplinary collaboration, while providing students and industry with valuable renewable energy experience.

U.S. DEPARTMENT OF ENERGY GEOTHERMAL COLLEGIATE COMPETITION

DOE's Geothermal Collegiate Competition invites teams from collegiate institutions to develop real-world geothermal solutions while competing for cash prizes and gaining valuable experience in the renewable energy industry.

The 2022 Geothermal Collegiate Competition winners were announced in FY22, but the second-place University of North Dakota and Reykjavik University team held their community engagement event in FY23. The team partnered with the Mandan, Hidatsa, and Arikara Nation to explore geothermal opportunities on tribal lands, including opportunities to repurpose existing oil and gas wells for geothermal energy and other cutting-edge concepts. NREL supported the execution of the community engagement events for the first- and second-place teams. Competition organizers traveled to New Town, North Dakota, for the University of North Dakota/Reykjavik University event, meeting with tribal leaders and community members.

2022 Geothermal Collegiate Competition winners pose with their award.
Photo courtesy of the University of Oklahoma

The 2023 Geothermal Collegiate Competition launched in May 2023 and the competition will take place during the fall 2023 academic semester. New in 2023, teams can choose from Technical or Policy tracks, and winners will be announced in early 2024. NREL also recruited geothermal industry experts as mentors for teams for the 2023 competition cycle, a new addition based on feedback from previous years.

AMERICAN-MADE GEOTHERMAL GEOPHONE PRIZE AND LITHIUM EXTRACTION PRIZE

NREL is administering two American-Made prizes on behalf of GTO: the Geothermal Geophone Prize and Lithium Extraction Prize.

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

The Geophone Prize launched on April 18, 2022, and is comprised of three progressive phases that will fast-track efforts to design, test, and fabricate advanced functional seismometer prototypes. Cash prizes are provided, and participants can access incubators, investors, universities, national laboratories, and others to help achieve their goals. The contests provide a total of $3.65 million in incentives—$2.55 million in cash prizes, $1.1 million in vouchers.

The three phases of the competition include concept and feasibility development, design and proof-of-concept, and prototype and test.

As part of prize administration, NREL executes informational webinars, communicates with competing teams, promotes the prize to potential competitors, administers payments, and manages the external review process.

Ten semifinalist teams advanced to the second phase of the competition, which is ongoing through December 2023. Up to five finalists will be announced and will proceed with phase three of the competition, where they will fabricate seismic sensor prototypes based on designs created during previous stages.

The American-Made Geothermal Lithium Extraction Prize is designed to find solutions that de-risk and increase market viability for direct lithium extraction (DLE) from geothermal brines. With global demand for lithium expected to increase by 500% by 2050 due to widespread adoption of electric vehicles and grid-scale battery storage, securing a domestic lithium supply is a crucial element in the clean energy supply chain.

Launched in April 2021, NREL has served as the prize administrator and logistical coordinator for the Lithium Extraction Prize, helping to recruit teams and encourage their progress. With support from the American-Made Network and cash prizes, NREL has supported innovators competing in the prize as they make strides in this key technology space.

The Geothermal Lithium Extraction Prize consists of three phases that will fast-track efforts to identify, develop, and test disruptive solutions to improve the profitability of DLE from geothermal brines. Each stage includes a contest period when participants work to rapidly advance their solutions. The prize is currently in its third phase and has a $4 million total prize pool. Both the semifinalists and five finalists for the FY23 competition have been chosen. NREL hosted a technical presentations event for the finalist teams in June 2023, and the final winners will be announced at the end of the fiscal year.

Impact: Advancements of DLE technologies allow for improved methods that lower costs, lessen environmental impacts, and further the mission to turn the threat of climate change into an opportunity to revitalize the U.S. energy and manufacturing sectors.

The Geothermal Lithium Extraction Prize has three separate phases across several years. *Figure by Joelynn Schroeder, NREL*

STATE OUTREACH AND STAKEHOLDER ENGAGEMENT

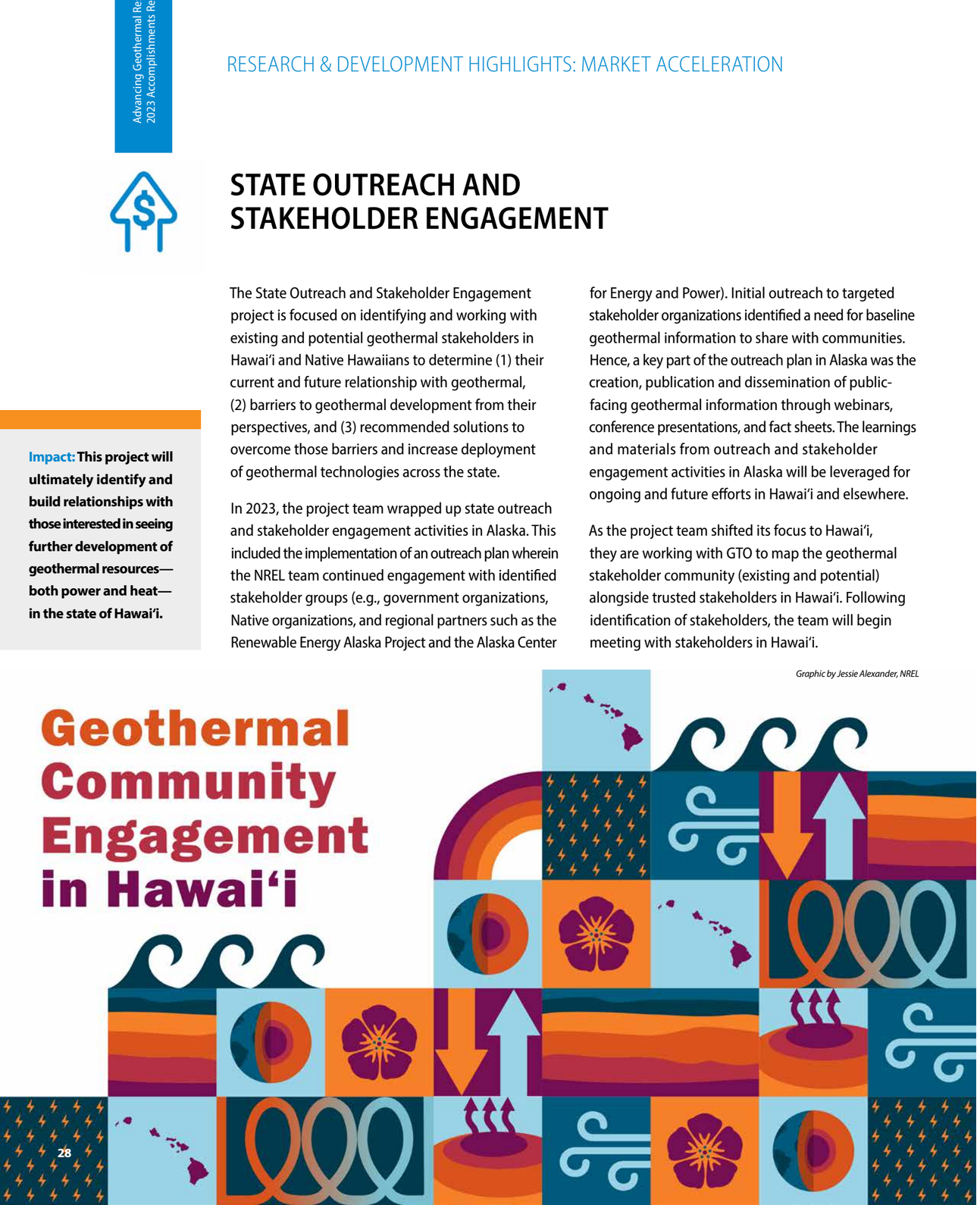
Impact: This project will ultimately identify and build relationships with those interested in seeing further development of geothermal resources—both power and heat—in the state of Hawai'i.

The State Outreach and Stakeholder Engagement project is focused on identifying and working with existing and potential geothermal stakeholders in Hawai'i and Native Hawaiians to determine (1) their current and future relationship with geothermal, (2) barriers to geothermal development from their perspectives, and (3) recommended solutions to overcome those barriers and increase deployment of geothermal technologies across the state.

In 2023, the project team wrapped up state outreach and stakeholder engagement activities in Alaska. This included the implementation of an outreach plan wherein the NREL team continued engagement with identified stakeholder groups (e.g., government organizations, Native organizations, and regional partners such as the Renewable Energy Alaska Project and the Alaska Center for Energy and Power). Initial outreach to targeted stakeholder organizations identified a need for baseline geothermal information to share with communities. Hence, a key part of the outreach plan in Alaska was the creation, publication and dissemination of public-facing geothermal information through webinars, conference presentations, and fact sheets. The learnings and materials from outreach and stakeholder engagement activities in Alaska will be leveraged for ongoing and future efforts in Hawai'i and elsewhere.

As the project team shifted its focus to Hawai'i, they are working with GTO to map the geothermal stakeholder community (existing and potential) alongside trusted stakeholders in Hawai'i. Following identification of stakeholders, the team will begin meeting with stakeholders in Hawai'i.

Graphic by Jessie Alexander, NREL



Advancing Geothermal Research
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RESEARCH & DEVELOPMENT HIGHLIGHTS: MARKET ACCELERATION

NREL LEADS GEOTHERMAL INTERAGENCY TASK FORCE TO ENGAGE STAKEHOLDERS ON PERMITTING CHALLENGES AND OPPORTUNITIES

NREL, on behalf of GTO, brought together federal and state regulators, geothermal industry representatives, environmental nongovernmental organizations, and tribal representatives as part of the Geothermal Interagency Task Force (Task Force) to discuss challenges and opportunities related to geothermal regulatory approvals and permitting. The Task Force included representatives from 11 federal agencies as well as state agencies in California and Nevada.

Over the course of the fiscal year, NREL organized and led meetings with the Task Force, invite-only forums with three subgroups, and listening sessions with representatives from nearly a dozen tribal nations. During these engagement activities, the NREL team provided guidance and context for the various groups, leveraging previous NREL work such as the non-technical barriers analysis. A final task force meeting culminated in an NREL technical report summarizing the committee's findings as a result of these meetings.

High-level recommendations for federal and state regulators included:

- Providing guides for developers that detail various parts of the permitting process, including guidance for geothermal development on public lands
- Developing a landscape-level view of the geothermal resource potential in the United States
- Improving interagency coordination, as well as tribal and stakeholder engagement
- Ensuring agencies have appropriate resources, including knowledgeable technical staff.

NREL's project team included Aaron Levine and Faith Martinez Smith with the final report available here: https://www.nrel.gov/docs/fy23osti/84684.pdf.

Partners: The Bureau of Land Management, U.S. Fish and Wildlife Service, Bureau of Indian Affairs, National Park Service, Bureau of Reclamation, U.S. Geological Survey, U.S. Department of Agriculture through the U.S. Forest Services, U.S. Department of Defense through the Military Aviation and Installation Assurance Sitting Clearinghouse and the U.S. Army Corps of Engineers, U.S. Department of Energy, and U.S. Environmental Protection Agency.

Impact: Engaging key stakeholders to address challenges related to geothermal regulatory approvals and permitting culminated in a set of recommendations to improve the process.

Business seminar. *Photo from Getty Images 157422738*

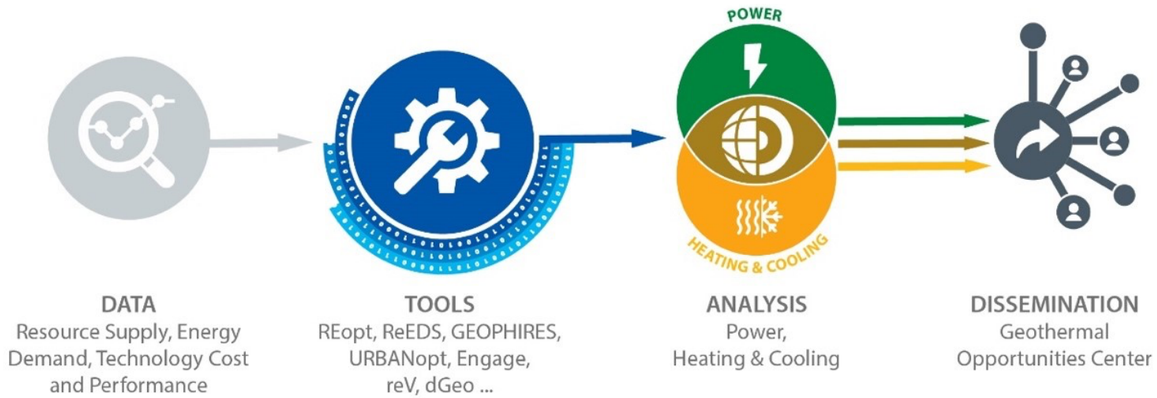
RESEARCH & DEVELOPMENT HIGHLIGHTS:
GEOTHERMAL GRID INTEGRATION RESEARCH PILLAR

3 YEAR PORTFOLIO: NREL KICKS OFF MODELING AND ANALYSIS PROJECTS TO UNDERSTAND GEOTHERMAL VALUE AND IMPROVE GEOTHERMAL REPRESENTATION

In 2023, NREL kicked off a 3-year, multiproject portfolio of modeling and analysis efforts to explore the value of geothermal grid integration, improve geothermal representation in flagship NREL modeling and decision tools that inform national-scale grid studies, and develop the baseline geospatial data sets needed by those tools. This program aims to represent geothermal at the same fidelity as solar and wind technologies for future-grid scenario studies that identify pathways to meet U.S. goals for widescale electrification and decarbonization.

Year 1 of this portfolio included modeling tool improvements, establishment of baseline geothermal heating and cooling (GHC) data sets and analyses (e.g., spatial and commercial deployment), and evaluation of geothermal technology deployment benefits to a decarbonizing grid, including grid demand reductions and grid services.

Years 2 and 3 of this portfolio will continue tool improvement with a focus on grid- and community-scale modeling tools, and will perform multiscale and multisectorial impacts and opportunity analyses of geothermal technologies. It will generate new geothermal power supply curves, establish market potential and grid benefits of specific technologies, establish new production cost model capabilities, and provide a complete assessment of the multiple roles that geothermal resources could play in a deeply decarbonized U.S. energy system.



Conceptual flow of data and activities within the 3-year Geothermal Modeling and Analysis Portfolio.

UNDERSTANDING VALUE AND COST METRICS FOR GEOTHERMAL THROUGH BASELINE GRID SERVICES

NREL researchers, led by Jonathan Ho, are using ReEDS, NREL's flagship electric power capacity expansion tool, to develop metrics and methods that quantify the value and competitiveness of geothermal power. The NREL analysis seeks to identify future scenarios that would impact the revenue from grid services provided by geothermal and reduced cost required for development, while accounting for substantial uncertainty about the future. The study examined how geothermal value changes with grid decarbonization, availability of nascent technologies (CO_2 capture and hydrogen), and land access barriers. The scenario analysis identified the growing role of capacity services for geothermal and found that combinations of technology, policy, and land use scenarios added significantly to geothermal value and development potential.

Impact: Developing baseline metrics and methods for evaluating the value and competitiveness of geothermal energy should improve understanding of the value of geothermal energy.

GEOTHERMAL REPRESENTATION INCORPORATED INTO NREL TOOLS

Geothermal technologies have been incorporated into a number of flagship and innovative NREL tools this year, expanding representation and improving the tools themselves. Following are high-level overviews and a featured example.

URBANopt™

NREL researchers Matt Mitchell, Brian Ball, Tanushree Charan, and Jing Wang led efforts to add networked ground source heat pump capabilities to URBANopt, a DOE-funded open-source modeling platform that simulates buildings and community-scale electrical and thermal networks. Adding these new capabilities allows users to design and simulate network ground source heat pump systems containing multiple buildings and ground heat exchangers.

Renewable Energy Integration and Optimization (REopt®)

A techno-economic decision support platform used by NREL researchers to optimize energy systems for buildings, campuses, communities, microgrids, and more, REopt recently incorporated geothermal heat pumps to its technology. These additions include

hybrid geothermal heat exchange, which allows for supplemental geothermal heat sink or source with a boiler or cooling unit, and a central plant geothermal heat pump. REopt recommends the optimal mix of renewable energy, conventional generation, and energy storage technologies to meet cost savings, resilience, emissions reductions, and energy performance goals, making it a valuable tool for its user base.

Regional Energy Deployment System Model (ReEDS)

NREL's flagship capacity planning model for the power industry, ReEDS simulates electricity sector investment decisions based on system constraints and demands for energy and ancillary services. The model is unique in its high-spatial resolution and advanced algorithms for representing the cost, value, and technical characteristics of integrating renewable energy technologies. The model reflects the unique regional attributes of energy production and consumption, considering various generating technologies, such as fossil, nuclear, and renewable technologies. Researchers recently examined impacts of national scale GHP to the electric power system using NREL's ReEDS model, analyzing impacts to the operation and investment in generation and transmission as well as emissions reduction potential. Adding geothermal technologies to this program expands its uses and capacities, helping to inform decision-making both inside and outside of the electricity sector.

Renewable Geothermal Energy Potential Model Development (reV)

NREL developed the reV model as a first-of-its kind detailed spatio-temporal modeling assessment tool to help utility planners, regional and national agencies, project and land developers, and researchers assess renewable energy resource potential. reV empowers users to calculate renewable energy capacity, generation, and cost based on geospatial intersection with grid infrastructure and land-use characteristics. Recently, researchers added a functional geothermal module that produces supply curves with similar fidelity as other technologies in reV.

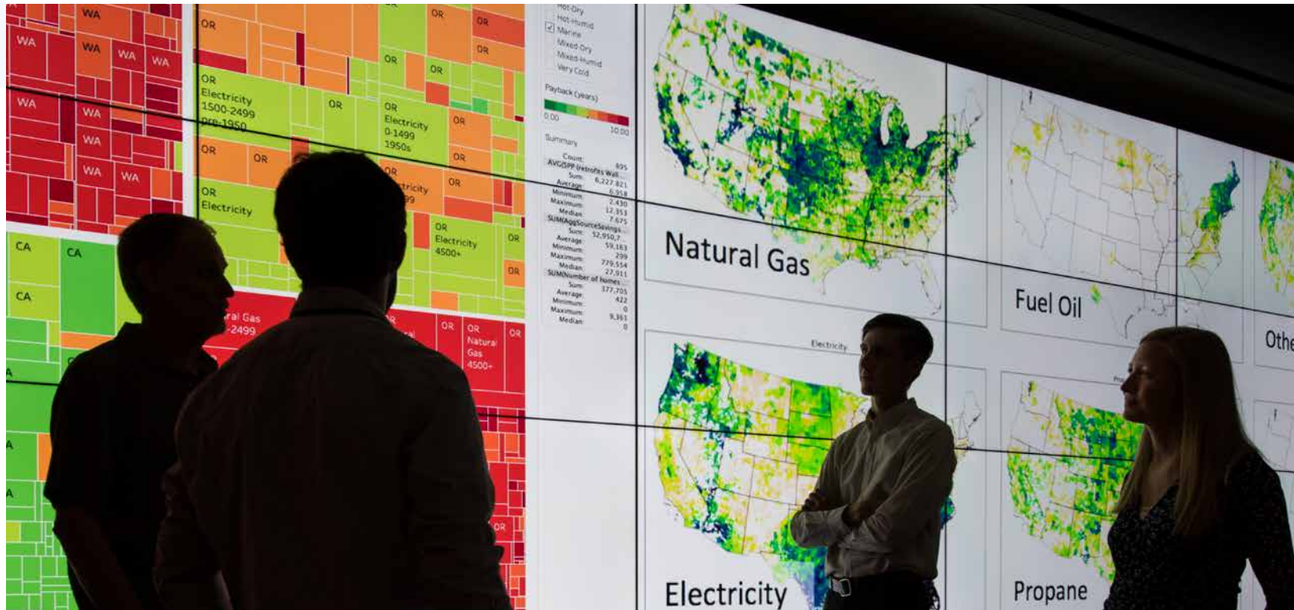
Engage™ Modeling Tool

Engage is a publicly available, free NREL tool that models energy systems with high shares of variable generation and storage across various geographic scales—from remote villages and urban districts to islands and entire continents. The tool makes cross-sectoral energy system planning and simulation more accessible for users by integrating visualization capabilities that illustrate the results of modeled scenarios to better understand the trade-offs and interdependencies involved in energy system transformations. The latest version of Engage offers built-in support for geothermal technologies, allowing users to easily model systems like binary cycle power plants through prebuilt, customizable templates. This recent update contains geothermal-specific inputs, allowing for an analytical depth that is comparable to specialized geothermal software such as the Geothermal Electricity Technology Evaluation Model (GETEM). Engage effectively integrates cross-sectoral energy planning, offering a comprehensive framework for in-depth analysis and strategic transformation of energy systems.

NREL-DEVELOPED BUILDING STOCK PLATFORMS INCORPORATE GEOTHERMAL HEAT PUMP REPRESENTATION

A new FY23 project has researchers Anthony Fontanini, Marlena Praprost, and Lauren Klun leading efforts to incorporate advanced geothermal heat pump (GHP) representation in popular building stock modeling tools developed by NREL.

The ComStock™ and ResStock™ programs 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 represent the majority of the commercial and residential building stock in the United States.



Craig Christensen, Joe Robertson, Eric Wilson and Stacey Rothgeb review the ResStock analysis tool. It is helping states, municipalities, utilities, and manufacturers identify which home improvements save the most energy and money. *Photo by Dennis Schroeder, NREL 45439*

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 data sets identify where energy is being consumed geographically, in what building types and end uses, and at what times of day. Simultaneously, it identifies the impact of efficiency measures: how much energy do efficiency measures save; where, or in what use cases do measures save energy; when, or at what time of day do savings occur; and which building stock segments have the biggest savings potential.

This technology has 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 this technology 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 timeseries data about future building stock scenarios with GHP systems.

With a total of 3,000 user accounts linked to the data viewer for ComStock and ResStock, incorporating geothermal technologies into this database has the potential to showcase GHP potential to a new audience. Coupled with NREL's expert knowledge of U.S. building stock—such as time series loads, peak demand, and impacts for a diverse set of buildings—this project is paving the way for geothermal technologies to become more mainstream for building owners and managers.

Currently, NREL researchers are incorporating GHP modeling into the available ComStock and ResStock upgrade measures.

Impact: Including geothermal technologies in building stock modeling programs illustrates how this resource can work with other renewable energy technologies to aid in decarbonization.

COMPILING BASELINE RESOURCE DATASETS TO IMPROVE GEOTHERMAL REPRESENTATION

NREL conducted the Geothermal Heating and Cooling Geospatial Datasets and Analysis project to assist stakeholders in evaluating the opportunities for geothermal heating and cooling technologies in the United States. These baseline datasets are necessary inputs to a larger portfolio of NREL modeling and analysis dedicated to demonstrating the value of integrating low-temperature geothermal heating and cooling technologies into national decarbonization plans. Most geothermal research has focused on high temperatures within the contiguous United States—this project is unique in that it collects data relevant to low-temperature geothermal resources. Low-temperature geothermal resources are defined by DOE as reservoirs – natural or engineered – with temperatures < 150 °C. These temperatures are used for multiple geothermal technology applications including geothermal heating and cooling (from geothermal heat pumps or geothermal direct use) as well as small-scale geothermal power production.

RESEARCH & DEVELOPMENT HIGHLIGHTS: GEOTHERMAL GRID INTEGRATION

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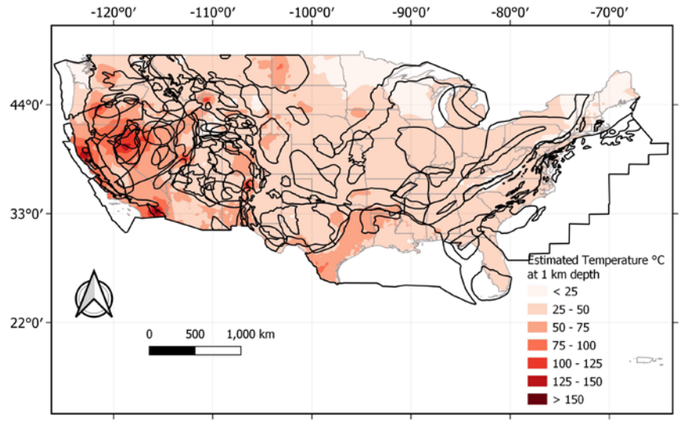
The first phase of this project focused on compiling and analyzing low-temperature geothermal datasets in the conterminous U.S., Alaska and Hawaii to generate an up-to-date baseline geospatial dataset of low-temperature resources. The second phase of this project focused on updating conceptual models and creating play fairway analysis (PFA) methodologies for low-temperature geothermal resources of different geothermal play types (e.g., sedimentary basin, radiogenic, and orogenic belt types) using relevant datasets collected in the first phase of this study. That "supply-side" baseline geospatial dataset will then be compared to "demand-side" datasets to provide accessible information on the potential of geothermal heating and cooling. These datasets together with the PFA methodologies can be utilized by a wide range of stakeholders, including energy modelers, communities, planners, and policymakers for evaluating and analyzing the potential for these low-temperature resources to de-risk geothermal exploration.

Notable contributions from this project include relevant data (e.g., calculated bottom-hole temperatures for oil and gas wells in Alaska), and workflows for low-temperature geothermal resources, drawing from the PFA methods previously developed for detecting hidden geothermal systems. Additional data are being compiled to assess repurposing oil and gas wells to contribute co-produced fluids toward geothermal direct use and geothermal heating and cooling resource potential. Future work could consist of creating favorability maps of low temperature geothermal resources (e.g., sedimentary basins, radiogenic, orogenic belt play types) for different regions in the U.S.

This project will facilitate analysis and future deployment of geothermal heating and cooling technologies by providing baseline data to community-led programs, and development approaches and workflows to stakeholders interested in accessing low temperature geothermal resources.

NREL researchers for this project included Estefanny Davalos Elizondo, Amanda Kolker, Nicole Taverna, and Emily Holt. The full technical report can be viewed here: https://www.nrel.gov/docs/fy23osti/87259.pdf.

Impact: The data and methodologies generated by this project will facilitate an increase in future deployment of geothermal heating and cooling technologies and provide baseline data for communities and stakeholders, helping to achieve national decarbonization goals.



Sedimentary basins in the conterminous United States (black outline) overlaid on the estimated temperature at 1 km depth. *Figure by Estefanny Davalos Elizondo*

NREL INVESTMENT IN GEOTHERMAL RESEARCH CAPABILITIES

Advancing Geothermal Research
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INTELLIGENT CAMPUS PROGRAM LOOKS INTO USING GEOTHERMAL TECHNOLOGY TO MEET NREL'S NET-ZERO OPERATIONAL GOALS

NREL Program Manager Michelle Slovensky describes Intelligent Campus as a research instrument. Focused on eliminating the greenhouse gas emissions produced by NREL's campus facilities, Intelligent Campus integrates clean energy sources like ground-source heat pumps into plant operations to meet decarbonization goals.

Intelligent Campus is assessing the conversion of NREL's South Table Mountain Campus's existing central plant—which currently consumes natural gas in order to supply all heating loads of eight major facilities—to non-carbon sources. Utilizing NREL-developed tools and researchers from NREL's Building Technologies and Science Center and the Energy Conversion and Storage Systems Center, the team is modeling an alternative thermal energy system to create a new district heating and cooling facility. These sources include geothermal borefields coupled with ground-source heat pumps, integrated with waste heat capture from NREL's high-performance computing center and state-of-the art HVAC technologies to reduce emissions to support buildings that serve simultaneously as research projects and operations assets.

Intelligent Campus evolves NREL's mission to advance the science and engineering of energy efficiency by combining geothermal energy, heat recovery, and electric boilers to meet the net-zero carbon goals of a community-like space. Using NREL's campus as a testing ground allows the team to explore how productive, efficient, and innovative the research and commercialization of these renewable energy assets can be in a controlled setting. Examining the interoperability of these technologies will yield a better understanding of how to adapt performance to meet demand in real time.

NREL's Intelligent Campus is exploring the integration of multiple renewable thermal energy streams (geothermal heat pumps, computer waste heat, and heat recovery chiller and cooling towers) into a campus-wide ambient loop. Coupling this concept with distributed energy resources for power (assets include hydrogen fuel cells, batteries, and solar array), NREL will demonstrate how to create a microgrid of emission-free technologies that will also make our campus and facilities more resilient.

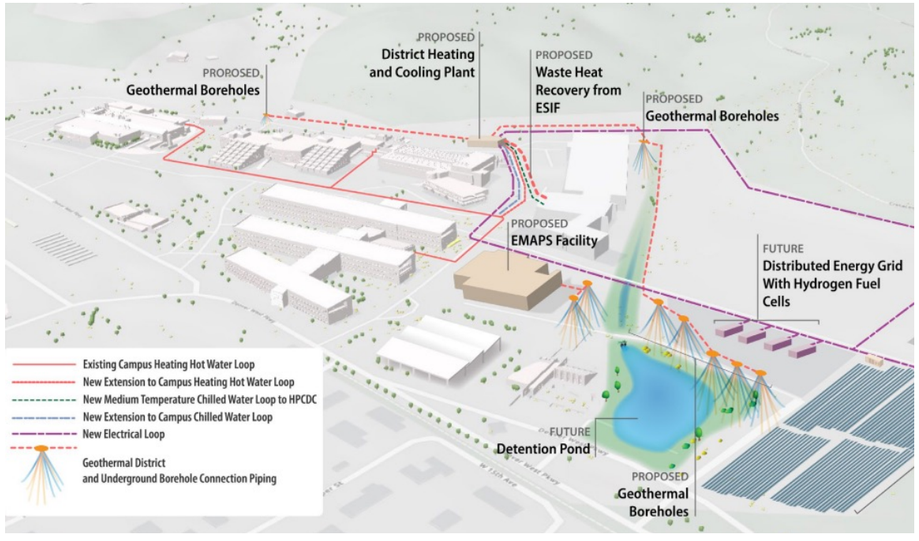
NREL's Intelligent Campus program enables researchers and energy managers to study the integration of renewable energy and energy efficiency technologies, make operational decisions that minimize emissions or enhance resiliency, and support a variety of research projects. *Photo by Joshua Bauer and Bryan Bechtold, NREL 80565*

INTELLIGENT CAMPUS, *CONTINUED*

By developing informatics and a digital "twin" of the campus, which creates an immersive mirror that shows how the campus functions in a digitized environment, researchers can compare performance goals against the actual performance of the technologies. This allows for better understanding of the interoperability of these energy assets, as well as better future planning. Through Intelligent Campus, NREL will meet its goals for the Flatirons Campus to reach net zero in FY23 and South Table Mountain Campus by FY26.

The team will proceed with drilling several test bores at various sites to retrieve data necessary for modeling efforts. Modeling will inform system design, and optimize production and annual performance of the geothermal resource. The data collected from this will allow NREL to make more informed decisions as its campuses grow, showcase how different sustainability technology can interact to achieve decarbonization goals, and help state and federal governments implement similar solutions for their own decarbonization problems. Lessons learned from Intelligent Campus will also help researchers fine-tune how similar geothermal infrastructure will function in a community.

Impact: Integrating geothermal technologies into NREL's operations not only aids in the lab's decarbonization goals but allows the campus to act as a research instrument, producing valuable data that can be used to understand geothermal infrastructure in a community setting.



Proposed additions for the NREL Intelligent Campus initiative. *Illustration by NREL*

Advancing Geothermal Research
2023 Accomplishments Report

GEOTHERMAL SHOWCASE: LIVING LABORATORY AT NREL MESA TOP

NREL researchers are installing new instrumentation at the "Geothermal Showcase" system deployed on NREL's Mesa Top Solar Radiation Research Laboratory (Mesa Top). The Mesa Top building has been successfully heated and cooled by a geothermal heat pump (GHP) system for over a decade and now the addition of new instrumentation will provide additional system data.

The Geothermal Showcase project was conceived in 2010 with the triple goal of providing renewable, low-cost heating and cooling to an NREL laboratory, creating a case study for on-site analysis of a GHP system and components, and spreading awareness and education of geothermal energy within NREL and the wider community. The system consists of 11 GHPs that have the capacity to cover the building's full heating and cooling load. The ground loop consists of 23 closed loop boreholes. Heat pumps, boreholes, piping, and system components were all installed with extensive instrumentation to be used for monitoring and analysis.

In 2023, additional data loggers and sensors were connected, along with the installation of a new data acquisition system (DAS). NREL will collect temperatures for the inlet and outlet of the boreholes and researchers also plan to measure the flow rates on each of the boreholes once appropriate meters are installed. These improvements will allow researchers to monitor and analyze the GHP system, spreading geothermal awareness and education.

Led by Matt Mitchell and Neil Popovich, this project leverages and builds on existing NREL infrastructure and DOE investment to create a public data set to encourage the implementation of GHP technology beyond the lab's campus. The collected data will provide GHP designers and researchers data to compare system performance and validate models so other campuses and communities can evaluate how similar systems would perform. The data will also be used to help researchers and the public understand the life cycle emissions benefits of GHP technology versus conventional heating and cooling systems.

Impact: New geothermal heat pump instrumentation at the Mesa Top Solar Radiation Research Laboratory allows more expansive analysis of NREL's successful geothermal system.

Photo of geothermal well field sensor data logger enclosure with un-terminated TC wires. *Photo by Amanda Kolker, NREL*

LEADERSHIP IN THE GEOTHERMAL SECTOR

February 24, 2023—The Honorable Governor Jared Polis tours NREL.
Photo by Joe DelNero, NREL 75262

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"HEAT BENEATH OUR FEET" INITIATIVE CONNECTS WESTERN U.S. WITH NREL GEOTHERMAL EXPERTISE

Colorado Governor Jared Polis launched "The Heat Beneath Our Feet" in FY23 to encourage renewable geothermal energy generation in Colorado and other western states. As part of this Western Governors' Association initiative, NREL provided technical assistance for the project and hosted an event on Feb. 24, 2023, showcasing the laboratory's geothermal research portfolio to more than 50 leaders in attendance, including the governor.

Gov. Polis and other attendees toured the Energy Systems Integration Facility and heard from distinguished speakers including Martin Keller, NREL director, Amanda Kolker, geothermal laboratory program manager, and Michelle Slovensky, intelligent campus program manager. The governor gave remarks on his initiative and attendees participated in roundtable discussions on transmission and grid integration, economic workforce development, and education and market development. The Western Governors' Association also hosted a webinar featuring Amanda Kolker following the event, addressing strategies for geothermal grid integration, opportunities to transition energy workers to geothermal, and ways to encourage market development and education.

February 24, 2023—The Honorable Governor Jared Polis, members of the Western Governors' Association, and staff from NREL gather in front of the Energy Systems Integration Facility for a group photo. The theme this year was Heat Beneath Our Feet—exploring geothermal energy.
Photo by Joe DelNero, NREL 75274

NREL REPRESENTS AT U.S.-ICELAND CLEAN ENERGY SUMMIT

On Sept. 21, 2022, Geothermal Program Manager Amanda Kolker represented NREL at the U.S.-Iceland Clean Energy Summit, held in Washington, D.C.

Hosted by the Embassy of Iceland, the Atlantic Council Global Energy Center, and Green by Iceland, the summit convened transatlantic government leaders, businesses, and civil society groups with the goal of strengthening international cooperation to achieve climate goals.

Kolker spoke on a panel titled "Harnessing geothermal energy potential and its cascading uses," alongside panelists from DOE, World Bank Group, Fervo Energy, Iceland's ON Power, and HS Orka. The panel discussed recent advancements in clean energy, including geothermal and carbon capture utilization/storage. Kolker brought NREL expertise to an international stage, highlighting geothermal as a triple resource: an energy source for heat and power, a storage method, and a potential supply of domestic minerals.

Impact: Connecting NREL leadership and research with a global audience aids rapid energy system decarbonization and international cooperation.

"Geothermal is not just an energy resource: it's a mineral resource, it's a storage resource, it's all these things. Our vision at NREL is to fully understand the value proposition, everything from electrons all the way to heat pumps, chemicals, minerals, and more."

– Amanda Kolker, NREL geothermal laboratory program manager at the US-Iceland Clean Energy Summit

September 21, 2022—"Harnessing geothermal energy potential and its cascading uses" panel at the U.S.-Iceland Clean Energy Summit in Washington, D.C. Amanda Kolker (NREL) sits third from left, in blue suit and brown shoes. *Image from the Atlantic Council Global Energy Center.*

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STANFORD GEOTHERMAL CONFERENCE

Nine NREL researchers traveled to Stanford, California, in February 2023 to spend a week sharing their latest advancements at the 48th Stanford Geothermal Workshop. The team—who authored nearly a dozen papers and presented 7 technical talks—exchanged with geothermal peers and industry experts from around the world on state-of-the-art geothermal research, development, and deployment.

Impact: This annual gathering of geothermal experts allows NREL researchers to share their latest findings and learn from other key researchers in the field.

Members of the NREL Geothermal Program pose for a group photo at the 48th Stanford Geothermal Workshop. *Photo by Amanda Kolker, NREL.*

STRATEGIC PARTNERSHIPS

Advancing Geothermal Research
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GEOTHERMAL STRATEGIC PARTNERSHIP PROJECTS IN FY23

CPS ENERGY IN SAN ANTONIO

The NREL geothermal team has several ongoing strategic partnership projects (SPP) in FY23 with industry and government agencies. One project is with the utility CPS Energy, based in San Antonio, Texas. For this project, the NREL team is conducting a geothermal resource assessment for the San Antonio region, evaluating the techno-economic feasibility of different geothermal technologies for electricity generation. In addition, the NREL team is tasked with holding an in-person workshop with the CPS Energy leadership team in San Antonio to present results on geothermal resource assessment and technologies, discuss potential geothermal opportunities for CPS Energy, and organize a roundtable discussion.

CONEDISON IN NEW YORK CITY

Another ongoing geothermal SPP project with a utility is a geothermal district heating feasibility study for ConEdison in New York City. ConEdison 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 geothermal resource assessment (estimating the local geothermal gradient and lithological investigations), as well as preliminary reservoir and surface plant integration simulations. Future work involves techno-economic analysis and providing guidance on permitting, well siting, and logistical challenges.

U.S. AIR FORCE AND THE U.S. ARMY

The NREL geothermal team also provides technical assistance to the Department of Defense (DoD), 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 DoD by providing third party evaluation of geothermal technologies for deployment at their military bases.

Two workers join residential geothermal heating/cooling pipe. *Photo from Getty Images 182387483*

GEOTHERMAL STRATEGIC PARTNERSHIP PROJECTS IN FY23, *CONTINUED*

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.

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 through multiple projects. This collaboration started several years ago and continues to this date. Examples of projects include development of geothermal training material 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.

LEGUP PROJECT

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 networked geothermal installations in Massachusetts as a pathway to decarbonize heating and cooling. The large project consortium includes national labs, universities, and industry partners. The installations will 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 larger team is analyzing these installations, considering technical and economic performance along with environmental, health, and equity impacts. NREL will be performing system-level modeling of the thermal loop, connected buildings, and borehole fields for improved understanding of the system control and operation.

Impact: NREL's strategic public-private partnerships develop high-impact, multiyear, multisector collaborations that drive transformation of domestic and global energy landscapes.

The partnerships bring together governments, communities, utilities, industry leaders, manufacturers, distributors, federal agencies—including the U.S. Department of Energy—and more.

https://www.nrel.gov/workingwithus/strategic-partnerships.html

NREL delegation visits Port Authority of New York and New Jersey.

In June, the LeGUp project team gathered in Framingham, MA where a networked geothermal system is being installed. In the photo, Eric Bosworth with Eversource explains the plan for the system where the thermal loop would run down the road and connect to the apartment buildings along it. Researchers are standing on the planned site for one of the three borehole fields attached to the system.

PUBLICATIONS AND COMMUNICATIONS

17,828
active users

24,960
total sessions

8,946
engaged sessions

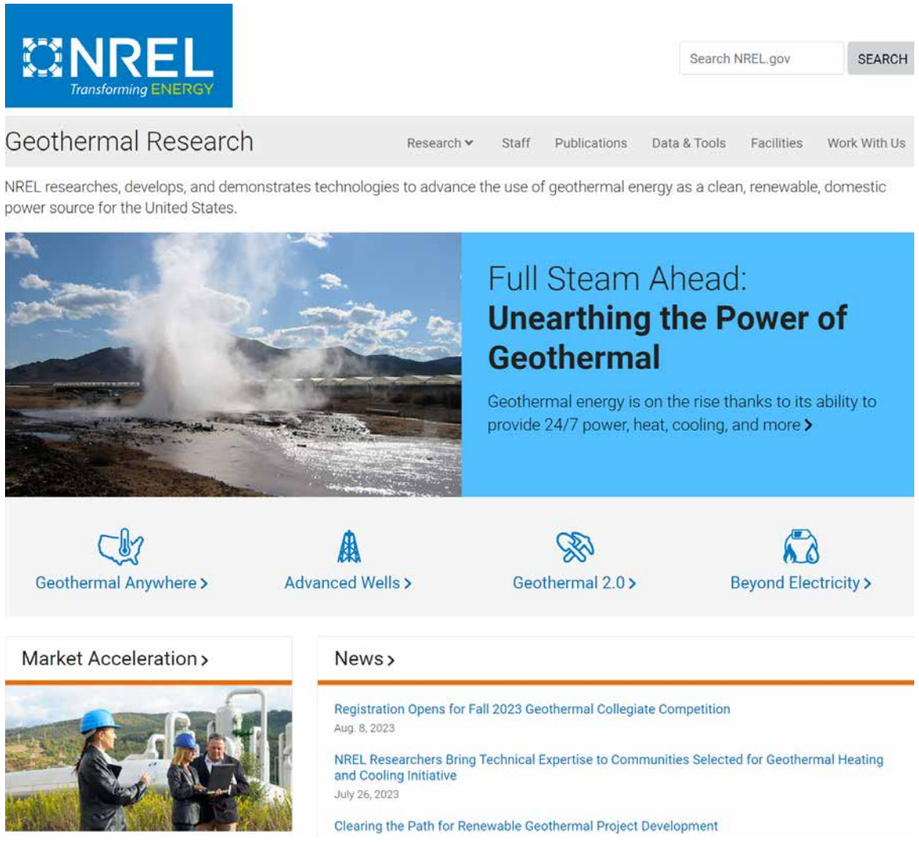
41,092
views

35.84%
engagement rate

GEOTHERMAL FEATURE STORY

In March 2023 the NREL communications team published a feature-length story focused on the geothermal research portfolio at the lab titled "Full Steam Ahead: Unearthing the Power of Geothermal".

The article led to 3,300 views, the most for an NREL news story in March, follow-on media stories with a reach of ~23,000,000, and more than 2,900 article opens through newsletter distribution.



WEBSITE ANALYTICS

TOP REFERRERS:

1. Google (56.7%)
2. Direct (26.9%)
3. Bing (6.3%)
4. Other (5.9%)

TOP ENGAGED SESSIONS BY STATE:

1. Colorado (734)
2. Texas (723)
3. California (548)
4. New York (312)
5. Virginia (196)

CHANNELS DRIVING ENGAGEMENT

1. Organic: 16,305 sessions
2. Direct: 6,646 sessions
3. Referral: 1,493 sessions
4. Social: 75 sessions
5. Email: 24 sessions

AVERAGE ENGAGEMENT

Time: 00:00:37

Engaged Sessions Per User: 0.50

Events per Session: 5.33

Views/Session: 1.65

Views per User: 2.3

NEW VS RETURNING USERS

New users: 11,600

Returning users: 6,228

USERS BY DEVICE TYPE:

1. Desktop (84.7%)
2. Mobile (14.4%)
3. Tablet (0.9%)

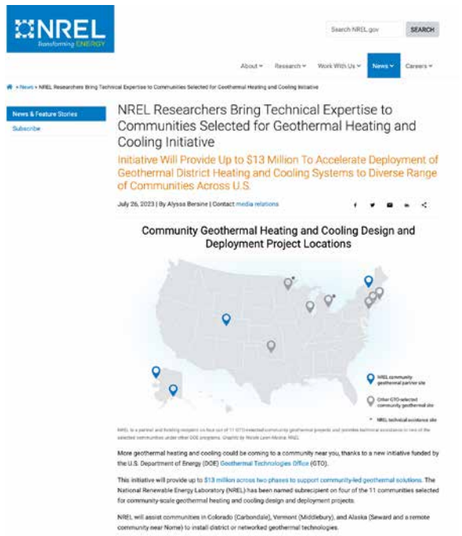
Website analytics reflect visits from October 1, 2022 to August 31, 2023.

There were 12,243 total users on the NREL geothermal website between October 2022 and August 2023, an increase of 46% compared to FY22. Page views in the same comparison period increased by 35%, reaching 30,377 total views.

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

OUTREACH THROUGH NREL.GOV PROGRAM NEWS STORIES

9 total news stories



"'Geothermal Is the Future'—University of Oklahoma Collegiate Competition Champions Host Geothermal Community Event." Oct. 10, 2022. https://www.nrel.gov/news/program/2022/geothermal-is-the-future-university-of-oklahoma-collegiate-competition-champions-host-geothermal-community-event.html

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"Full Steam Ahead: Unearthing the Power of Geothermal." March 7, 2023. https://www.nrel.gov/news/features/2023/full-steam-ahead-unearthing-the-power-of-geothermal.html

"NREL-Led Team Explores Potential of Underground Geothermal Energy Storage for All Seasons." March 9, 2023. https://www.nrel.gov/news/program/2023/nrel-led-team-explores-potential-of-underground-geothermal-energy-storage-for-all-seasons.html

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"NREL Researchers Bring Technical Expertise to Communities Selected for Geothermal Heating and Cooling Initiative." July 26, 2023. https://www.nrel.gov/news/program/2023/nrel-researchers-bring-technical-expertise-to-communities-selected-for-geothermal-heating-and-cooling-initiative.html

"Registration Opens for Fall 2023 Geothermal Collegiate Competition." August 8, 2023. https://www.nrel.gov/news/program/2023/registration-opens-for-the-fall-2023-geothermal-collegiate-competition.html

SOCIAL MEDIA CONTENT, IMPRESSIONS, AND ENGAGEMENT

***Content posted to NREL social media channels, including Twitter, Facebook, Instagram, and LinkedIn.**

94 total posts
236,475 impressions

2,726 reactions
222 shares
54 comments
4,293 link clicks
6,869 video views

**October 2022 through August 2023*

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MEDIA MENTIONS

1,124 MEDIA HITS
related to NREL and geothermal

~1,032,521,770
individuals reached

NOTABLE MEDIA:

"Idle Oil Wells' Next Act? Becoming Batteries for Renewable Energy." Bloomberg. Reach: ~25.3 million.

"Using Energy from the Earth to Power the Earth," 9 News Denver. Reach: ~3 million

"The Power Beneath – Zeroing In: Carbon Neutral 2050." NHK World-Japan.

"Electric-Powered Cars, Hydrogen-Powered Trucks, and Hydro-Powered Cities—Plus Geothermal!" Transforming Energy: The NREL Podcast.

"Estudiantes podrían ganar hasta $10,000 al participar en competencia de Geotermia" Telemundo.

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2. Robins, Jody C., Devon Kesseli, Erik Witter, and Greg Rhodes. 2022. "2022 GETEM Geothermal Drilling Cost Curve Update: Preprint." Presented at the 2022 Geothermal Rising Conference, Reno, NV, August 28–31, 2022. NREL/CP-5700-82771. https://www.nrel.gov/docs/fy23osti/82771.pdf
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5. Davalos Elizondo, Estefanny, Amanda Kolker, and Ian Warren. 2023. "Low-Temperature Geothermal Geospatial Datasets: An Example from Alaska: Preprint." Presented at the 48th Stanford Geothermal Workshop, Stanford, CA, February 6–8, 2023. NREL/CP-5700-85035. https://www.nrel.gov/docs/fy23osti/85035.pdf
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7. Pauling, Hannah, Adam Schultz, Esteban Bowles-Martinez, Xiaolei Tu, Chet Hopp, Alain Bonneville, and Amanda Kolker. 2023. "Exploring for Superhot Geothermal Targets in Magmatic Settings: 2022 Field Campaign at Newberry Volcano." Presented at the 48th Stanford Geothermal Workshop, Stanford, CA, February 6–8, 2023. NREL/CP-5700-85001. https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2023/Pauling.pdf
8. Taverna, Nicole, Jon Weers, Jay Huggins, Sean Porse, Arlene Anderson, Zach Frone, and RJ Scavo. 2023. "Improving the Quality of Geothermal Data Through Data Standards and Pipelines Within the Geothermal Data Repository: Preprint." Presented at the 48th Stanford Geothermal Workshop, Stanford, CA, February 6–8, 2023. NREL/CP-6A20-84994. https://www.nrel.gov/docs/fy23osti/84994.pdf
9. Trainor-Guitton, Whitney, Drew Siler, and Bridget Ayling. 2023. "Temperature Uncertainty Modeling with Proxy Structural Data as Geostatistical Constraints for Well Siting: An Example Applied to Granite Springs Valley, NV, USA." Presented at the 48th Stanford Geothermal Workshop, Stanford, CA, February 6–8, 2023. NREL/CP-5700-84926. https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2023/Trainorguitton.pdf
10. Wendt, Daniel, Ghanashyam Neupane, Juliet Simpson, Guangdong Zhu, and Joshua McTigue. 2023. "Hybrid Natural Gas Geothermal Combined Cycle Power Plant Analysis." Presented at the Society of Petroleum Engineers' Energy Transition Symposium. August 22–23, 2023. NREL/CP-5700-86610. https://www.nrel.gov/docs/fy23osti/86610.pdf
11. Zhu, Guangdong, Dayo Akindipe, Joshua McTigue, Erik Witter, Trevor Atkinson, Travis McLing, Ram Kumar, Pat Dobson, Mike Umbro, Jim Lederhos, and Derek Adams. 2023. "Techno-economic Analysis and Market Potential of Geological Thermal Energy Storage (GeoTES) Charged With Solar Thermal And Heat Pumps Into Depleted Oil/gas Reservoirs and Shallow Reservoirs: a Technology Overview." Presented at the Society of Petroleum Engineers' Energy Transition Symposium. August 22–23, 2023. NREL/CP-5700-86609. https://www.nrel.gov/docs/fy23osti/86609.pdf

CONFERENCES AND EVENTS

- International Ground Source Heat Pump Conference
- Stanford Geothermal Workshop
- Geothermal Rising Annual Meeting
- International District Energy Agency Annual Conference
- USGS City-Scale Geothermal Powell Center Workshop
- Western Governors' Association Heat Beneath Our Feet Tour
- GEOTHERMICA Workshop for DEEPEN Consortium
- EGS Earthshot Launch and Summit
- Western Governors' Association Heat Beneath Our Feet Webinar
- Geothermal Rising Conference and Meeting with Secretary Granholm
- NREL Industry Growth Forum
- International Energy Workshop
- ARPA-E Innovation Summit
- Geothermal Transition Summit
- American Geophysical Union Fall Meeting
- International Symposium on Supershot Resource Assessments
- DEEPEN Superhot Workshop
- ASHRAE Winter Conference
- ASHRAE Annual Conference
- 3D Seismic Symposium

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12. Levine, Aaron. 2023. "Pathways to Overcome Geothermal Deployment Barriers." Golden, CO: National Renewable Energy Laboratory. NREL/FS-6A20-85219. https://www.nrel.gov/docs/fy23osti/85219.pdf

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13. Weers, Jon. 2022. "Collaborative Data Management for Science, R&D (Citation Only)." NREL/PR-6A50-83728.

14. Prilliman, Matt. 2023. "GETEM in the System Advisor Model (SAM)." January 19, 2023. NREL/PR-7A40-85131. https://www.nrel.gov/docs/fy23osti/85131.pdf

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16. Levine, Aaron. 2023. "Non-Technical Barriers to Geothermal Development in California and Nevada." May 24, 2023. NREL/PR-6A20-86307. https://www.nrel.gov/docs/fy23osti/86307.pdf

17. Beckers, Koenraad, Kevin McCabe, and Hyunjun Oh. 2023. "Introducing dGeo 2.0: updated distributed geothermal supply, demand and adoption model for evaluating potential of geothermal district heating and cooling systems." IDEA 2023.

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18. Akindipe, Dayo, Jody C. Robins, Erik Witter, Koenraad Beckers, Mohammed Alnasser, Daniel Croce, Luis Zerpa, and Alfred W. Eustes III. 2023. Drilling Efficiency Analysis Based on Experience at Ormat's McGinness Hills Geothermal Field (NREL Internal Use Only). NREL/TP-5700-83371.

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21. Levine, Aaron, Ligia E. P. Smith, Jody Robins, Erik Witter, Caity Smith, and Clare Haffner. 2022. Non-Technical Barriers to Geothermal Development in California and Nevada. NREL/TP-6A20-83133. https://www.nrel.gov/docs/fy23osti/83133.pdf

22. Oh, Hyunjun, and Koenraad Beckers. 2023. Cost and Performance Analysis for Five Existing Geothermal Heat Pump-Based District Energy Systems in the United States. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-86678. https://www.nrel.gov/docs/fy23osti/86678.pdf

23. Davalos Elizondo, Estefanny, Amanda Kolker, and Nicole Taverna. 2023. Assessing Low-Temperature Geothermal Play Types: Relevant Data and Play Fairway Analysis Methods. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-87259. https://www.nrel.gov/docs/fy23osti/87259.pdf (In publication)

24. Levine, Aaron, Faith Martinez Smith, and Heather Buchanan. 2023. Topics and Considerations for Developing State Geothermal Regulations. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-86985. https://www.nrel.gov/docs/fy23osti/86985.pdf (In publication)

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27. Jahnke, Ben, Hiroki Sone, Hao Guo, Chris Sherman, Ian Warren, Corne Kreemer, Clifford H. Thurber, and Kurt L. Feigl. 2023. "Geomechanical analysis of the geothermal reservoir at San Emidio, Nevada." Geothermics. JA-5700-86262. https://doi.org/10.1016/j.geothermics.2023.102683

ADVANCING GEOTHERMAL RESEARCH

FISCAL YEAR 2023 ACCOMPLISHMENTS REPORT

SEPTEMBER 2023

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Transforming ENERGY

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