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Geothermal Energy R&D: An Overview of the U.S. Department of Energy's Geothermal Technologies Office

Geothermal energy can provide answers to many of America's essential energy questions. The United States has tremendous geothermal resources, as illustrated by the results of the DOE GeoVision analysis, but technical and non-technical barriers have historically stood in the way of widespread deployment of geothermal energy. The U.S. Department of Energy's Geothermal Technologies Office within the Office of Energy Efficiency and Renewable Energy has invested more than $470 million in research and development (R&D) since 2015 to meet its three strategic goals: (1) unlock the potential of enhanced geothermal systems, (2) advance technologies to increase geothermal energy on the U.S. electricity grid, and (3) support R&D to expand geothermal energy opportunities throughout the United States. This paper describes many of those R&D initiatives and outlines future directions in geothermal research. [DOI: 10.1115/1.4049581]

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Introduction

Geothermal energy can provide answers to many of America's essential energy questions. The "heat beneath our feet" is an always-on source of secure, reliable, and flexible domestic energy that can be used across industrial, commercial, and residential sectors. The use of geothermal energy can also offer important benefits to the nation, including grid stability, greater diversity in the portfolio of affordable energy options, thermal energy storage, critical materials, and efficient heating and cooling solutions.

Geothermal is a renewable resource, with a nearly inexhaustible supply. Current U.S. installed electricity-generating capacity is more than 3.8 gigawatts (GW) [1]. Estimates of our nation's technically recoverable resource potential include approximately 30 GW of new, undiscovered hydrothermal resources and 100+ GW of new geothermal energy accessible through enhanced geothermal systems [2–4].

However, technical and non-technical barriers have historically stood in the way of widespread deployment of geothermal energy. The U.S. Department of Energy's (DOE's) Geothermal Technologies Office (GTO) within the Office of Energy Efficiency and Renewable Energy (EERE) funds R&D to overcome those barriers.

Geovision Analysis and Results

To better understand the potential for and pathways to increased geothermal use across the U.S. energy portfolio, GTO conducted the *GeoVision* analysis—a multi-year research collaboration among National Laboratories, industry experts, and academia. The analysis assessed opportunities to expand geothermal energy deployment, calculated economic benefits to the U.S. geothermal industry and the potential environmental benefits of increased deployment, and investigated opportunities for desalination, mineral recovery, and hybridization with other energy technologies for greater efficiencies and lower costs.

The *GeoVision* analysis illustrated that geothermal is America's untapped energy giant. Key findings about the potential for geothermal energy—summarized in the 2019 report, *GeoVision: Harnessing the Heat Beneath Our Feet*[2]—include:

- Improving technologies that reduce the costs and risks of geothermal development could increase geothermal power generation nearly 26-fold from today, representing 60 gigawatts-electric (GWe) of electricity-generation capacity by 2050.
- The market potential for geothermal heat pump (GHP) technologies in the residential sector is equivalent to supplying heating and cooling solutions to 28 million households—14 times greater than existing installed capacity.
- The economic potential for district-heating systems is more than 17,500 installations nationwide, compared to the 21 total district-heating systems installed in the United States as of 2017.
- Improving permitting timelines alone could increase installed geothermal electricity-generation capacity to 13 GWe by 2050—more than double the 6 GWe projected in the business-as-usual scenario that serves as the baseline for the analysis.

The GeoVision analysis showed that to realize these outcomes, geothermal energy must overcome significant barriers. Primary among these challenges is the subsurface nature of geothermal, which leads to both technical barriers (e.g., the need for better exploration technologies) and non-technical barriers (e.g., land access and permitting). Economic competitiveness with other energy sources is critical. GTO's mission is to increase deployment of geothermal energy through R&D that addresses these barriers and identifies innovative technologies that enhance exploration and production while reducing cost and risk.

Geothermal Technologies Office and Our Strategic Goals

Geothermal Technologies Office is one of the 11 technology offices within EERE, which leads DOE's efforts to create and sustain American leadership in the transition to a global clean

[2]The *GeoVision* report can be found at: www.energy.gov/GeoVision

energy economy. Statutory authority for GTO comes from the Energy Policy Act of 2005[3] and the Energy Independence and Security Act of 2007.[4] These authorities and GTO's contribution support DOE's mission to ensure America's security and prosperity by addressing its energy, environmental, and nuclear challenges through transformative science and technology solutions.

Energy Efficiency and Renewable Energies vision is a strong and prosperous America powered by clean, affordable, and secure energy. GTO's research portfolio contributes to EERE's advancement of its priorities: energy affordability, energy integration, and energy storage. To align with these priorities and help America realize geothermal energy's many current and potential contributions to the U.S. energy sector, GTO has outlined three strategic goals as the basis of its research portfolio for the next five years. These goals link to crucial areas of research on the pathway to geothermal deployment.

> **Unlock the potential of enhanced geothermal systems.**
>
> Enhanced geothermal systems (EGS) are engineered reservoirs, created where there is hot rock but little to no natural permeability or fluid saturation present in the subsurface. The GeoVision analysis confirms that EGS resources have the potential to provide game-changing electric sector contributions—with a total potential resource base of more than 100 GWe [2–4]. EGS technologies can also support significant growth within the non-electric sector for district heating and other direct-use applications. GTO is focused on research critical to enabling EGS—most notably through the Frontier Observatory for Research in Geothermal Energy (FORGE) initiative, for technologies that facilitate characterization, development, and sustained production over reservoir life cycles.
>
> **Advance technologies to increase geothermal energy on the U.S. electricity grid.**
>
> As noted above, GTO is supporting R&D of technologies to enable EGS—the long-term basis for exponential utility-scale geothermal deployment growth. At the same time, GTO is also focused on opportunities for more geothermal energy on the grid; specifically, research to capture undiscovered U.S. hydrothermal resources. GTO is pursuing technical improvements in exploration and drilling, as well as assessing non-technical barriers such as permitting timelines that currently limit development.
>
> **Support R&D to expand geothermal energy opportunities throughout the United States.**
>
> Geothermal resources are available at varying depths and temperatures throughout the United States. As of 2020, geothermal power plants are concentrated in the western United States, with the majority located in California and Nevada. Deep-EGS capabilities are essential to make geothermal electricity-generating capacity available nationwide and are a critical area of focus for GTO's long-term research portfolio. However, through advanced resource characterization and optimized system designs that incorporate site supply and demand profiles, GTO seeks to unlock the vast potential for moving to a true 50 state energy solution. GTO supports growth in these technologies by researching advances in efficiency, building partnerships with federal and non-federal stakeholders, and helping to identify and solve non-technical barriers.

Major Geothermal Technologies Office Initiatives 2015–2020

During the last six years, GTO has funded over $470 million in R&D aimed at meeting the three objectives listed above. In this section, we describe the biggest research initiatives of this period (in alphabetical order). Where publications are available, they are included as references; however, many projects are relatively new and do not yet have published results.

[3]Energy Policy Act (EPact) 2005, P.L. 109-58, §931(a)(2)(C) (42 USC 15801).

[4]Energy Independence and Security Act (EISA) 2007, P.L. 110-140, Title VI, Subtitle B, § 611 (42 U.S.C. 16231(2)(C)).

Advanced Energy Storage Initiative/Energy Storage Grand Challenge (ESGC), Including Beyond Batteries, Deep Direct-Use (DDU), and Bi-Directional Energy Storage Using Low-temperature Geothermal Applications. In support of the DOE's Grid Modernization Initiative, GTO has made major investments in reservoir thermal energy storage (RTES), cements, and GHP RD&D. This research will move the United States toward the GeoVision 2050 goals of 1700 geothermal direct heating and cooling systems and 48 million geothermal heat pump systems—most of which are projected in the eastern United States. GTO projects under the ESGC focus on researching more flexible (hybrid) geothermal systems, validating feasibility of these systems, and demonstrating flexible storage benefits to offset peak demand. Research also includes innovative ground source heating and cooling applications that are critical to minimizing impacts from intermittent energy sources and providing an on-demand "earth battery."

In large portions of the United States, direct use geothermal applications have the potential to provide cost-effective, renewable thermal energy with a cascade of potential uses, from electricity generation to direct heating and cooling, industrial and commercial applications, and agricultural uses. In particular, DDU has the potential to deliver direct geothermal from deep, lower-temperature resources nationwide, thus expanding direct geothermal to new domestic markets. Starting in 2017, GTO supported six projects that conducted feasibility studies of large-scale, low-temperature deep-well geothermal systems coupled with advanced direct-use applications. This initiative examined the techno-economic feasibility of DDU projects in geologically distinct parts of the country, with projects covering the Appalachian Basin (NY/WV) [5,6], Columbia River Basalt Group (OR) [7], Cotton Valley Group (TX) [8], and the Illinois Basin (IL) [9] in addition to a project in the Wassuk Range (NV) [10]. These feasibility studies were finalized in 2020 and GTO is currently working on an analysis of this portfolio.

In 2018 and 2019, DOE's national laboratory researchers began partnering with industry and geothermal stakeholders to develop energy storage (as an alternative to battery storage) and "behind-the meter" generation, storage and electric load shaping technologies. An example of this approach is the RTES research underway at Lawrence Berkeley National Lab and UC Berkeley aimed at providing communities varying degrees of behind-the-meter heating and cooling and a reduction of peak-load [11]. Another example is Oak Ridge National Laboratory's efforts aimed at developing two novel underground thermal energy storage technologies integrated with electric-driven heat pumps to enable flexible behind-the-meter demand of buildings while meeting their thermal demands with increased energy efficiency [12].

Alternative storage technologies developed to increase flexibility on the generation side also have the potential for application via direct use. For example, Idaho National Laboratory, partnering with researchers at Lawrence Berkeley National Laboratory and the University of Idaho, is studying the potential for using excess heat from large, inflexible thermal power stations in a synthetic geothermal reservoir to allow these power stations to reduce electrical power output while remaining connected to the grid during periods of high variable renewable availability. While a pre-existing hydrothermal resource is not necessary to obtain the benefits of the RTES system, co-locating one with a low-temperature geothermal resource would improve the efficiency of the power cycle and the economic viability of such resources, and increase low-temperature geothermal resource development in the United States [13].

Next, GTO built on the 2017, 2018, and 2019 efforts by shifting its foundational work toward demonstrating innovative energy storage and use technologies. GTO put out a call for proposals for Bi-directional Energy Storage Using Low-temperature Geothermal Applications in early 2020, which included DDU, RTES, and other geothermal direct use and energy storage technologies. This research solicitation moves the needle forward, from feasibility studies toward the systems engineering and demonstration phases, to enable new, more resilient energy services. This will lead to alternatives to grid-dependent heating and cooling that also add resilience to the larger energy system in which they operate. An award was made recently to Cornell University; this project will construct and test an exploratory borehole to ground-truth the use of deep, direct-use geothermal at Cornell in Ithaca, NY and will use this lower-temperature geothermal resource for base load heat to meet seasonal peak demand.

Critical Materials. Beyond the traditional value that geothermal resources can provide for electricity or thermal applications, tapping into geothermal brines for valuable byproducts including critical materials presents a promising opportunity. Since 2014, GTO has funded two competitively awarded R&D solicitations focusing on mineral recovery from geothermal brines through novel extraction technologies, as well as better resource characterization for critical materials and rare earth elements in U.S. geothermal resources [14]. However, commercial demonstration of mineral recovery from geothermal brines has not advanced beyond pilot scale, and details of process and performance are known only to Intellectual Property (IP) owners and operators (including partly DOE-funded pilot demonstrations). In addition to supporting novel technology development, GTO recognizes the important co-location potential of hidden geothermal systems and critical materials deposits, and how acquiring data that supports the identification of these upstream resources is of significant strategic importance. GTO is exploring opportunities to enhance the collection of data that leads to improved understanding of the distribution of lithium and other critical materials, as well as hidden geothermal resources, by enabling utilization of advanced machine learning techniques. GTO has also partnered with DOE's Advanced Manufacturing Office (AMO) and Vehicle Technologies Office (VTO) to tackle the technical and operational challenges associated with the U.S. battery supply chain, including a June 2020 workshop and a request for information. This partnership represents an opportunity for GTO to identify impactful research and performance metrics for developing future research pathways for GTO specifically, as well as integrated across broader EERE supply chain research.

Efficient Drilling for Geothermal Energy (EDGE). Drilling operations can account for half of the cost to develop a geothermal project and the GTO has supported early-state R&D in drilling and well construction for decades. Drilling rates in geothermal wells are notoriously low and the most recent initiative, known as EDGE, focuses on improving the average daily rate of penetration (ROP) in geothermal drilling. Average drilling rates account for all the time it takes to drill a well to depth, including non-productive time (NPT) that necessarily reduces average drilling rates. The ongoing EDGE initiative (started in 2018) focuses on the following: (1) the reduction of NPT; (2) the development of technologies to improve penetration rates while drilling ahead; and (3) innovative approaches to accelerate learnings to improve geothermal drilling performance.

A total of ten projects were selected as part of the EDGE initiative. While many of these projects overlap in their focus (e.g., projects that address ROP also can reduce NPT), all the focus areas are addressed in EDGE. The University of Oklahoma is developing advanced loss-circulation methods and materials to help with wellbore strengthening, specifically addressing NPT issues in geothermal wells [15]. Early-stage R&D directed at improving drilling rates includes development of advanced materials for drill bits at Argonne National Laboratory; advanced downhole motor development using elastomer-free piston motors for downhole rotation and downhole determination of ROP at Sandia National Laboratories [16]; downhole sensing and event-driven sensor fusion for depth-of-cut based autonomous response and drilling optimization at Sandia National Laboratories; data-driven drilling optimization methods from Oklahoma State University [17] and Texas A&M University; alternative rock reduction methods at Texas A&M; and high-temperature sensor development (gyroscopes) needed for measurement-while-drilling and hole surveying [18]. Success of any of the projects directed at improving ROP will also result in reduced NPT, because it will help improve drilling efficiency and drilling tool life. To accelerate learnings, Oregon State University is in the early stages of leading an effort to assimilate a robust domestic and international geothermal drilling dataset that can use machine learning to identify optimized drilling performance practices, and the University of Texas at Austin has established the Geothermal Entrepreneurship Organization (GEO) to support bringing oil and gas expertise into the geothermal arena. GEO recently sponsored a week-long workshop, PIVOT 2020, that focused on transitioning oil and gas capabilities to support geothermal development.

Enhanced Geothermal Systems Collab. Geothermal Technologies Office designed a major initiative, EGS Collab, to develop intermediate-scale, heavily instrumented test beds to obtain data and improve the understanding of subsurface fracture stimulation methods as well as the flow of fluids through these fractures and heat transfer from the rock to these fluids. These data and associated learnings would be used to exercise and test conceptual and numerical models in support of full-scale initiatives such as the FORGE effort discussed below. This large effort led by Lawrence Berkeley National Laboratory and Sandia National Laboratories, includes numerous other National Laboratories, universities, and private companies.[5] Collaboration between the geothermal reservoir modeling community, experimentalists, geologists, geophysicists, engineers of various disciplines, and data scientists is a cornerstone of this highly integrated effort, from experiment planning to execution of field activities to analysis of results. The experimental sites are located in the Sanford Underground Research Facility (SURF) in Lead, South Dakota (at the former Homestake Gold Mine), which is managed by the South Dakota Science and Technology Authority.

In the first experiment, conducted at a level of the facility at 4850-foot (1478 m) deep, the goal was to establish a fracture network that connects an injection well and a production well via hydraulic fracturing with stimulation pressures exceeding the minimum principal stress, that is, the creation of mode 1 fractures. Eight sub-horizontal holes about 60 m in length were drilled: one for fluid injection, one for fluid production, and six heavily instrumented monitoring holes. All the holes were continuously cored, logged with a full suite of tools, and fully instrumented to monitor the stimulation and flow experiment. Following a series of controlled stimulation tests, hydraulic characterization of the created fracture system, and tracer testing performed during the last half of 2018, both long-term ambient-temperature water flow tests and chilled-water flow tests with interspersed tracer tests were performed in 2019 and early 2020 creating a rich data set to exercise the predictive capabilities of models needed for full-scale EGS development [19].

To accommodate other experimental activities at SURF and to perform experiments in a different rock type and stress regime, a second experimental test bed is being developed on the 4100-ft depth level; while the 4850-ft level exhibits largely heavily foliated phyllites, less foliated blocky amphibolites make up the bulk of the rock on the 4100-ft level. This second test bed will be used to attempt initiation of shear stimulation along existing discontinuities. Planning for this test bed is ongoing, with drilling expected to begin in early 2021.

Frontier Observatory for Research in Geothermal Energy (FORGE). Geothermal Technologies Office's flagship FORGE initiative includes a dedicated field site where scientists and engineers will be able to develop, test, and accelerate breakthroughs in EGS technologies and techniques. FORGE is a critical step toward creating a commercial pathway to EGS because it will promote transformative and high-risk science and engineering

[5]More information on EGS Collab can be found at: https://openei.org/wiki/EGS_Collab_Project_Overview

Critical Research Areas

	Stimulation Planning and Design	Fracture Control	Reservoir Management
Definition	Research that supports efforts to design and optimally stimulate a well in accordance with natural subsurface characteristics	Research that supports efforts to develop an optimal fracture network as well as increase understanding of the resulting fracture system	Research that supports efforts to sustain long-term heat exchange in the system
Core R&D Actions	• Develop new **well configurations and well field designs** for optimal reservoir stimulation and operation • Develop **new and adapt existing fracturing technologies** and **procedures** for EGS	• **Optimize design of fracture procedures** to reservoir conditions • Develop **alternative injection practices and procedures** • Understand the effect of different **stimulation types** on the resulting fracture system • Develop methods for successful **zonal isolation** during stimulation at high temperatures and pressures	• **Predict and monitor changes** in the fractures system over time • Engineer **solutions to compromised or other unwanted changes** in reservoir permeability that can disrupt operation
Supporting R&D Actions	• Quantify **vertical and horizontal stress** at higher resolution • Correlate **wellbore stress measurements** beyond the wellbore • Correlate **in situ elastic rock property measurements** beyond the wellbore • **Reduce uncertainty** of optimized residence times and reservoir volumes	• **Predict induced seismicity** with higher reliability and accuracy • **Predict changes** in permeability, volume, conductivity, and other factors impacting heat exchange during fracture creation • Conduct **real time in situ monitoring** of key variables to track stimulation and heat exchange potential	• Incorporate in situ, **permanently installed monitoring instrumentation** in wellbore • Develop **active reservoir management** processes, procedures, and tools, including zonal isolation, to avoid thermal breakthrough and optimize flow rate • Resolve **fracture connectivity** and estimate reservoir volume

Fig. 1 Critical research areas for GTO's FORGE

through the development and testing of cutting-edge technologies, which the private sector is not financially equipped to undertake. FORGE will bridge lessons learned from past DOE-funded and international EGS field demonstrations, and R&D portfolios. With broad collaboration among academia, industry, and national labs, FORGE facilitates optimization and validation of EGS technologies. Initiated in 2015, the FORGE initiative is currently in Phase 3. Phases 1 and 2 included a larger number of potential teams and sites, with a down-select to the University of Utah, and Milford, Utah, as the final team and site during Phase 2.[6]

Phase 2 also included the development of the FORGE R&D Roadmap,[7] which laid out research priorities for Phase 3. GTO tasked an outside group to research, design, and develop a roadmap for the FORGE initiative, with the objective of the roadmap to provide technical research recommendations to GTO, FORGE, and the broader research community. The Roadmap provided both Critical Research Areas (Fig. 1)—Stimulation Planning and Design, Fracture Control, and Reservoir Management—as well as Enabling R&D focus areas and Implementation Principles.[8]

The five-year Phase 3 period (started Q4 2019) will comprise all technical, administrative, and logistical tasks necessary for management and oversight of FORGE operations and tasks specific to the solicitation, selection, testing, and evaluation of new and innovative EGS tools, techniques, and supporting science. In spring 2020, the University of Utah released the first of the Annual FORGE solicitations open to the community for the opportunity to develop technologies and methodologies to be tested at the Utah site; proposals to this solicitation are currently under review. The FORGE project is anticipated to be ongoing through 2024, with competitive solicitations released on an annual basis.

Geothermal Prizes. To attract the interest of a wider range of researchers, GTO has instituted two prizes with the program. Prizes offer administrative advantages over other DOE financial assistance, including streamlined project timelines.

Geothermal Student Competition: A critically important goal of GTO is the technical training of the American workforce through Science, Technology, Engineering, and Math (STEM) education. The geothermal space presents a diverse and powerful suite of opportunities for new job creation, requiring a workforce that is technically skilled in a variety of subjects, including geoscience, engineering disciplines, data analytics, and electricity generation. The GeoVision report details the importance of education programs

[6]More information on the Utah FORGE site can be found at: https://utahforge.com/

[7]The Roadmap can be found at: https://www.ida.org/-/media/feature/publications/f/fo/forge/d-10474.ashx

[8]https://www.ida.org/-/media/feature/publications/f/fo/forge/d-10474.ashx

in raising public awareness of the benefits of geothermal technology through education programs, improving public acceptance of geothermal technologies, and increasing market penetration and deployment. Raising public awareness involves engaging new audiences and increasing the number and diversity of geothermal advocates and consumers. GTO views student groups, both K-12 and at university, as key to expose to geothermal technologies. Through an annual Student Competition, GTO, in conjunction with the National Renewable Energy Laboratory (NREL), seeks to generate interest and encourage students to pursue a career in geothermal energy and more broadly to promote geothermal and subsurface science literacy. The 2020 Competition focused on a non-technical barrier to geothermal development to foster understanding and share the benefits of geothermal energy technologies. Student teams used geographic information system (GIS) mapping to create a compelling infographic/poster or interactive maps to discover potential opportunities from geothermal resources. GTO plans to issue two competitions per year starting in the fall of 2020.[9]

Geothermal Manufacturing Prize: The American-Made Geothermal Manufacturing Prize is a set of four contests designed to spur innovation and address manufacturing challenges fundamental to operating in harsh geothermal environments. The prize leverages additive manufacturing innovations to push the boundaries in how to design, fabricate, and operate geothermal tools, equipment, and componentry, in pursuit of 60 GWe of projected geothermal capacity by 2050, as outlined in the GeoVision report. Along the way, incentives in the form of cash prizes, technical vouchers, and subsidized field testing will be available to contest winners. The prize is also supported by the American-Made Network—a pioneering effort to gather and engage more than 130 of America's energy incubators, investors, universities, 17 National Laboratories, and others to help prize participants achieve their goals.[10]

Geothermal Wells of Opportunity: Amplify. Stimulation activities are central to the success of EGS; injection of fluid expands the permeable surface area accessible in the subsurface, increasing heat exchange between the fluid and hot rock, and thus increasing reservoir energy output and well productivity. Well stimulation creates a productive geothermal reservoir where only hot rock existed previously. Historically, most EGS stimulations involved activating a single zone or multiple zones of fractures from an open-hole section of the wellbore. In these cases, fluids are pumped downhole, creating or re-opening fractures enough to cause shearing.

A shift in the thinking surrounding EGS stimulation strategy—progressing from open-hole stimulation (as described above) to isolated stimulation zones—has occurred since the completion of the previous DOE-funded EGS field demonstration projects. Through the Amplify effort, GTO seeks to validate new stimulation techniques and technologies that can move the sector beyond open-hole stimulations, implementing a number of new technologies or those adopted from the oil and gas sector that have shown promise for improving stimulation success in EGS wells. Testing these new methods in idle or unproductive wells located in and on the margins of existing geothermal fields provides a near-term opportunity to generate power, adding to the economic viability of each geothermal field.

In July 2020, three Amplify projects were selected to field test a variety of stimulation methods, with the potential to produce over 20 MWe. This program will also include seismic monitoring networks at each of the stimulation sites to help identify the stimulated reservoir volume as well as monitor and mitigate induced seismicity.

[9]More information on the 2020 Geothermal Student Competition, called the *Geothermal Design Challenge™: GIS Mapping Student Competition can* be found at: https://inl.gov/geothermalchallenge/

[10]More information on the Geothermal Prize can be found at: https://www.herox.com/GeothermalManufacturing

Machine Learning for Geothermal Energy. The rapidly advancing field of machine learning offers substantial opportunities for technology advancement and cost reduction throughout the geothermal project lifecycle, from resource exploration to power plant operations. GTO is funding 11 projects to help establish the practice of machine learning in the geothermal industry and maximize the value of the rich datasets utilized in the geosciences.Artificial intelligence (AI) and machine learning (ML) can enhance geothermal resource discovery, drilling, and power plant management by identifying patterns in complex data and by optimizing decision-making processes. For example, GTO-funded R&D projects are integrating machine learning into resource exploration workflows. In this research, sophisticated algorithms can enhance large, remotely sensed datasets using sparse subsurface data, aiding in the discovery of hidden hydrothermal resources [20,21]. Other GTO R&D is attempting to revolutionize subsurface characterization in geothermal areas by utilizing neural networks to analyze seismic data and image underground features that control subsurface fluid flow [22,23]. The resulting imagery can then be used to better target subsurface permeability prior to drilling.

Geothermal Technologies Office is also funding three projects that apply advanced analytics to power plant datasets, with the goal of improving operations and resource management [24,25]. Utilizing machine learning technologies to analyze operational power plant and reservoir data can increase energy production. For example, so-called digital twin models of a reservoir can allow operators to simulate the effects of many different production strategies, and use the results to help develop an optimized approach. These models are made possible by training neural networks on data collected at power plants over multiple decades. When sufficient training data are available, algorithms can capture and simulate the core behavior of a subsurface resource with sufficient fidelity to provide an extremely valuable simulation tool for operators. Decision making is improved by allowing for easy evaluation of multiple scenarios.

Similarly, AI/ML can improve the efficiency of geothermal drilling by helping to optimize drilling parameters and by providing early warning of events that can lead to drilling failures. Drilling operations generate data from a variety of surface and downhole sensors, and AI can analyze this information to identify signs of drilling dysfunction or impending trouble.

Play Fairway Analysis and Exploration R&D: Hidden Geothermal Systems in the Basin and Range. A major barrier to the development of the large geothermal resources in the United States is the difficulty in locating blind hydrothermal systems, due to the high cost and risk of drilling in areas with no obvious surface signs of a resource. GTO has made a priority of advancing the state of the art in exploring for blind hydrothermal systems, and key among these technologies is the concept of play fairway analysis (PFA). Already successfully used in the oil and gas sector, play fairway analysis can be a key tool for decision making in any exploration project. GTO's efforts to adapt play fairway methods for use in geothermal exploration, with the ultimate goal of quantifying and reducing risk in geothermal exploration, have been very successful to date.

Geothermal Technologies Office began its PFA initiative in 2014 with a goal of developing methods to pinpoint high-grade potential drilling areas using combinations of data sets. The initiative comprised of three phases, which moved progressively from desktop study of large (regional) areas using existing data, to field work and new data collection at select highly prospective sites, to a final drilling validation that confirmed three new resource discoveries. The diversity of sites explored is shown on the map in Fig. 2.

By conducting PFA in unexplored or underexplored regions, or by using new play concepts in basins with known geothermal potential, GTO investments quantified and reduced uncertainty in geothermal exploration—another step toward the potential 30 GW of additional power from energy hidden deep in the Earth. That

Fig. 2 Original full set of Play Fairway Analysis sites, showing the diversity of geographic areas covered

highly successful effort yielded many favorable prospects that will require further study to unlock their potential [26–30]. Following the successful PFA research initiatives, GTO is sponsoring a large-scale RD&D initiative designed to transform geothermal exploration in the Basin and Range region of the United States. This project will assemble the necessary tools, data, and practices for finding hidden resources in the Great Basin and make them accessible to all in a regional geologic playbook. This tool will significantly lower the bar to entry for explorationists, and speed the development of undiscovered resources in the area. In other areas of the United States, the groundwork for similar projects is being laid through early-stage R&D aimed at improving conceptual models of less-well-understood resource types. This work—carried out in partnership with the DOE labs—will provide a basis for future campaigns to focus on volcanic provinces, including Hawaii and the Pacific Northwest.

Waterless Stimulation. The most commonly applied wellbore stimulation technology, hydraulic fracturing, relies heavily on water-based fracturing fluids due to the general availability and low cost of water as well as its capability for proppant transport. GTO has been interested in developing stimulation methods that require little to no water—reducing the usage needed for geothermal progress and easing constraints on fresh water consumption. In addition, in certain crosscutting applications with oil and gas, there is growing concern over the amount of water disposed after similar operations have been completed. Starting in 2018, GTO began funding three National Laboratory projects in waterless stimulation investigating anhydrous energetic stimulation (Sandia National Laboratories and Lawrence Livermore National Laboratory) [31]; a novel stimulation fluid—water-based polyallylamine + CO_2—that combines to form a less water-intensive hydrogel (Pacific Northwest National Laboratory) [32]; and pulsed injection of a foam-based stimulant (Oak Ridge National Laboratory) [33].

Zonal Isolation for Manmade Geothermal Reservoirs. Zonal isolation technologies can radically improve the performance and economics of EGS or manmade geothermal reservoirs, addressing some of the barriers to commercialization of EGS systems. These technologies provide the ability to target specific zones for stimulation activities, which can enable command and control of fracture location and economy of resources. In turn, this reduces development costs and operational risks associated with EGS development and facilitates more power from fewer wellbores. Effective and reliable zonal isolation remains one of the most critical technology needs to enable widespread EGS development.

Geothermal Technologies Office is funding four R&D efforts that focus on the creation of new zonal isolation technologies and the modification of existing zonal isolation technologies for use in EGS stimulations that can operate in high-temperature, geochemically challenging environments. These projects include: a redesign of an existing zonal isolation barrier by eliminating the use of elastomers and transitioning to an all-metal design (Welltec, Inc); upgrading an existing drillable frac plug to withstand much higher temperatures (Fervo Energy); working toward fully retrievable high-temperature packer systems using thermally degradable expandable foaming agents for isolation behind slotted wellbore liners (Hotrock Energy Research Organization (HERO)); and development of a first-of-its-kind technology for in situ, rapid and durable multistage zonal isolation using functionalized graphene nanoribbons embedded in high-performance polymers, which will be irradiated with a microwave tool (C-Crete Technologies) [34]. The R&D efforts underway have resulted in initial prototypes of zonal isolation technologies, and these technologies should be ready for testing in geothermal reservoirs following the conclusion of the projects.

Future Research Directions

The GeoVision study included the GeoVision Roadmap: a compilation of technical, economic, and institutional actions across the geothermal community—DOE, industry, academia, and other stakeholder groups—that can help address barriers and ensure the continued contribution of geothermal energy as a renewable and diverse energy solution for the United States. The Roadmap was meant to serve as a guide that the collective geothermal community can use to meet those key objectives and allow the nation to harness the potential offered by geothermal resources.[11]

Building from the GeoVision Roadmap, GTO will continue to fund RD&D across research areas outlined in Table 1 to meet research objectives that support GTO key strategic goals to unlock the potential of enhanced geothermal systems, increase geothermal electrons on the U.S. electricity grid, and expand geothermal energy opportunities throughout the country. Research areas and the associated objectives outlined in Table 1 not only provide enough structure to guide GTO focus on specific research activities, but also allow GTO to adapt activities to changing market and

[11]https://www.energy.gov/sites/prod/files/2019/06/f63/5-GeoVision-Chap5-opt.pdf

Table 1 Future geothermal technologies office research directions by research area and objective

Research area	Objective
Exploration and characterization	Improve resource targeting for all geothermal resource types
Subsurface accessibility	Improve drilling costs towards the "ideal" cost curves used in the *GeoVision* analysis
Subsurface enhancement and sustainability	Enhance and sustain geothermal energy recovery
Resource maximization	Accurately capture the value of geothermal energy resources
Data, modeling, and analysis	Expand the capabilities of data use to identify and address barriers to geothermal deployment

technology conditions. In the near term, GTO will be conducting a significant amount of field-based research across the GTO portfolio. This work, in conjunction with the very early-stage R&D that is analysis- and lab-based, provides an unprecedented opportunity to empower public access to robust cutting-edge field datasets, as well as accelerate pathways for meeting EERE priorities and GTO strategic goals.

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