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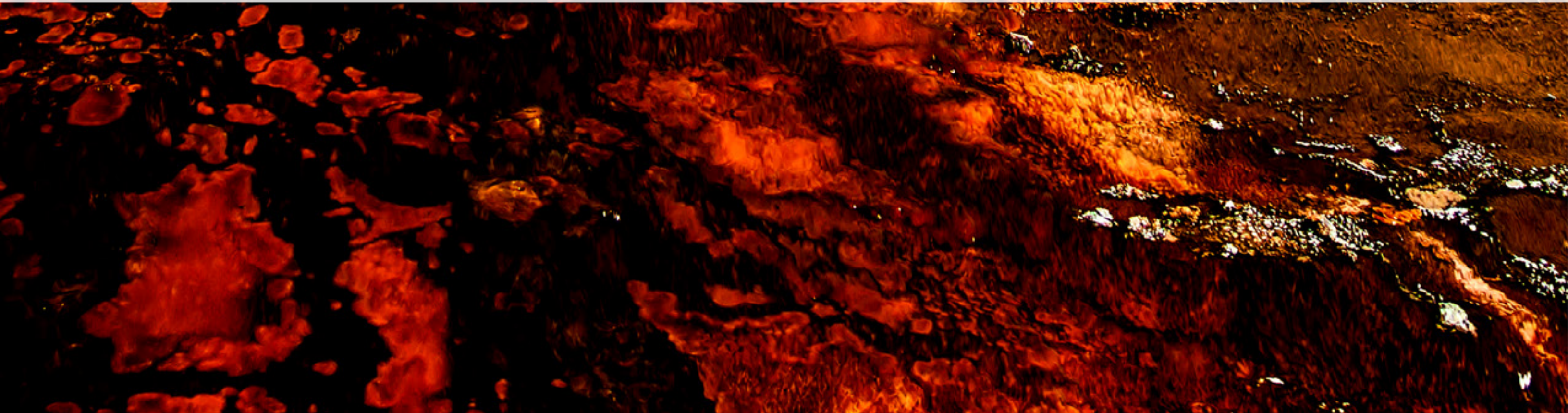
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

GEOTHERMAL TECHNOLOGIES OFFICE

Fiscal Years 2022–2026

MULTI-YEAR PROGRAM PLAN



Disclaimer

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List of Acronyms

BAA	balancing authority area
dGEO	Distributed Geothermal Market Demand model
DMA	Data, Modeling, and Analysis (subprogram in Geothermal Technologies Office)
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy (at DOE)
EGS	enhanced geothermal system(s)
EISA	The Energy Independence and Security Act of 2007
EPAct	The Energy Policy Act of 2005
FORGE	Frontier Observatory for Research in Geothermal Energy
FY	fiscal year
GeoDAWN	Geoscience Data Acquisition for Western Nevada
GETEM	Geothermal Energy Technology Economic Model
GDH	geothermal district heating
GHP	geothermal heat pump
GPRA	Government Performance and Results Act
GTO	Geothermal Technologies Office
GW	gigawatt(s)
GW_e	gigawatts-electric
GW_{th}	gigawatts-thermal
H_2	hydrogen
MMT	million metric tons
MWth	megawatts-thermal
MYPP	Multi-Year Program Plan
NREL	National Renewable Energy Laboratory
OPC	ordinary Portland cement
PDC	polycrystalline diamond compact (cutters)
PFA	Play Fairway Analysis (initiative)
PPA	Power Purchase Agreement
RD&D	research, development, and demonstration
ReEDS	Regional Energy Development System
SLOPE	State and Local Planning for Energy
USGS	United States Geological Survey
WOO	Wells of Opportunity

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Executive Summary

Geothermal energy—the "heat beneath our feet"—is a firm, flexible source of clean, secure, and reliable domestic energy that can be utilized across industrial, commercial, and residential sectors. Geothermal energy offers important benefits to the nation, including grid stability, greater diversity of affordable energy options, efficient heating and cooling, key technology and workforce pathways from oil and gas to renewable geothermal development, and lower carbon emissions to help transition Americans to a carbon pollution-free power sector by 2035 and a net-zero emission economy by 2050, while ensuring the clean energy economy benefits all Americans.

The U.S. Department of Energy's (DOE) Geothermal Technologies Office (GTO) works in partnership with industry, academia, DOE's national laboratories, and other stakeholders to increase deployment of geothermal energy resources through research, development, and demonstration (RD&D) targeting geothermal exploration and production. GTO focuses on accelerating innovation and expanding opportunities across the geothermal resource spectrum: from low-temperature and direct-use resources to the frontier of enhanced geothermal systems (EGS). GTO conducts research under its most recent statutory authorizations: The Energy Act of 2020 [Title III, Section 3002], the Energy Independence and Security Act of 2007 (EISA) [Title VI, Subtitle B, § 611] and the Energy Policy Act of 2005 (EPAct) [Section 931(a)(2)(C)]. The Energy Act of 2020, which mainly modified the EISA, authorizes RD&D across the geothermal spectrum, including hydrothermal resources, EGS, and low-temperature applications, as well as work in critical materials, thermal energy storage, integrated energy systems, technical assistance, and stakeholder outreach and education. EISA outlines geothermal energy research activities as related to the Act's Accelerated Research and Development statutes, while EPAct provides the basis for RD&D and commercial application for geothermal technologies—specifically calling for research to develop improved technologies for reducing the costs of geothermal energy installations.

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 for geothermal stakeholders to expand geothermal energy deployment, as well as calculated economic benefits to the U.S. geothermal industry and the potential environmental impacts of increased deployment. The analysis also 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 in the race to achieve ambitious climate progress. Key findings about the future for geothermal energy are summarized in the 2019 report *"GeoVision: Harnessing the Heat Beneath Our Feet"* and include the potential for a 26-fold increase in geothermal power generation by 2050, a market potential for geothermal heat pumps (GHPs) to supply 28 million households with heating and cooling solutions, and economic potential for geothermal district heating (GDH) systems up to 17,500 installations. Geothermal deployment in the electric and nonelectric sectors combined could reduce greenhouse gas emissions equivalent to removing 26 million cars from U.S. roads annually. The *GeoVision* analysis also showed the criticality of improving permitting timelines and demonstrated potential to grow clean energy jobs and local economic benefits.

To realize deployment growth such as that outlined in the *GeoVision* analysis, 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 nontechnical barriers (e.g., land access and permitting).

This document, the GTO Multi-Year Program Plan (MYPP), builds on the findings of the *GeoVision* analysis, outlining a 5-year plan of activities GTO will pursue to support the growth and long-term contribution of geothermal energy to the U.S. electricity grid and American homes and buildings. The MYPP outlines GTO's vision and mission and presents a high-level technology plan for key areas of GTO research starting in Fiscal Year (FY) 2022 and running through the end of FY 2026. This research plan supports GTO's contributions toward the opportunities outlined in the *GeoVision* analysis.

GTO considers the key findings of the *GeoVision* analysis to be clear evidence of geothermal energy's role as a critical enabling technology in the nation's aggressive, zero-carbon energy transformation.

Thus, GTO has adopted the following Strategic Goals to reach geothermal energy's full potential:

> **Strategic Goal 1:** Drive toward a carbon-free electricity grid by supplying 60 gigawatts (GW) of EGS and hydrothermal resource deployment by 2050.
>
> **Strategic Goal 2*:*** Decarbonize building heating and cooling loads by capturing the economic potential for 17,500 GDH installations and by installing GHPs in 28 million households nationwide by 2050.
>
> **Strategic Goal 3:** Deliver economic, environmental, and social justice advancements through increased geothermal technology deployment.

In addition to this Executive Summary, the MYPP includes the following sections:

The Opportunities for Geothermal Energy (Section 1): Briefly describes geothermal technology and its value to the United States; outlines GTO's role within the DOE's Office of Energy Efficiency and Renewable Energy (EERE); and summarizes GTO's vision, mission, Research Areas, Strategic Goals, and how the office organizes around strategic research and deployment focuses.

Geothermal Technologies Office Technology Plan (Section 2): Outlines GTO's primary Research Areas that cut across GTO's structure, including challenges and barriers, highlighted performance goals, and high-level topics of expected research through FY 2026. The Research Areas are:

- Exploration and Characterization
- Subsurface Accessibility
- Subsurface Enhancement and Sustainability
- Resource Maximization
- Data, Modeling, and Analysis
- Geothermal Integration and Awareness

Program Evaluations
(Section 3): Describes GTO's anticipated evaluative information needs and types of priority evaluation activities, e.g., peer review.

The MYPP will serve as an operational guide to help GTO strategically plan and execute research and development activities and will serve as a resource to help communicate to stakeholders and the public GTO's 5-year priorities and opportunities that will allow geothermal energy to contribute to a carbon pollution-free electric sector by 2035 and a net-zero emission economy by 2050. The Research Areas discussed in the MYPP provide the foundation for GTO's research activities. As presented in the MYPP, these Research Areas and the topics discussed in each are intended to provide enough structure to guide research activities while also allowing GTO to adapt activities to changing market and technology conditions. Research Areas in the MYPP ultimately support GTO's key Strategic Goals discussed previously. GTO's intent is to revisit this MYPP around FY 2024 to assess progress and identify areas of potential revision. The level of revision will depend largely on technology advancement and market changes, updates to DOE and EERE priorities, and GTO's progress toward highlighted performance goals. As noted, the plan outlined in the MYPP is intended to provide a solid basis for research while allowing GTO to adapt readily to a dynamic domestic and global energy landscape.

1 The Opportunities for Geothermal Energy

1.1 Geothermal Energy's Role in Addressing the Climate Crisis

By 2050, deployment of carbon-free geothermal energy can help address the climate change crisis by offsetting more than 500 million metric tons (MMT) of greenhouse gases in the electric sector and more than 1,250 MMT in the heating and cooling sector—combining for the equivalent of replacing 26 million cars on the road every year (U.S. DOE 2019).

In the power sector, geothermal deployment can grow to provide 60+ gigawatts-electric (GW_e) of firm, flexible clean energy by 2050, with a major expansion of geothermal power production in and outside the western half of the United States, where commercial geothermal power plants are currently concentrated (Augustine et al. 2019).

In the heating and cooling sector, geothermal heat pumps (GHPs) can be deployed in 28 million U.S. households by 2050, serving close to 25% of the entire U.S. heating and cooling market (Liu et al. 2019). GHPs represent a deployment-ready technology that offers a crucial pathway to decarbonize heating and cooling for single family homes, campuses, and cities across the United States.

Geothermal district heating (GDH), where geothermal energy heats buildings through a distribution pipeline network, has the promise to offset fossil fuel used for heating individual, commercial, and industrial buildings. By 2050, up to 17,500 GDH systems can be deployed in population centers along the U.S. Eastern Seaboard, the Ohio Valley, Texas, and portions of the Southwest, serving 45 million households (McCabe et al. 2019).

However, these significant deployment opportunities will not happen without intervention. If geothermal develops along a "business as usual" pathway, only minimal growth and market share by 2050 will be realized—less than 1% in the electric sector and 7% in heating and cooling.

Geothermal's power sector outlook will be positively impacted by streamlined regulations and policies that place geothermal on par with other clean energy generation technologies through tax incentives and clean energy standards. However, the major step-change in deployment—to allow geothermal to provide 60+ GW_e of firm, flexible clean energy—relies on technology advancements across the geothermal life cycle, from de-risking exploration to lower-cost drilling and improved reservoir development to accurately capturing geothermal energy's market value as a firm, flexible clean energy resource.[1]

The promise of geothermal heating and cooling to support deep decarbonization is also clear but will require improvements to both technology performance as well as increases in overall public awareness and consumer acceptance. For both GHPs and GDH, demonstration and deployment at scales ranging from isolated communities to grid-connected urban environments will validate system performance and underscore geothermal's value to contribute toward decarbonizing heating and cooling loads, lowering peak energy demands, and improving site resilience. GDH technologies will also benefit from step-change advancements in geothermal power production to enable more efficient exploration, drilling, and reservoir production. For all geothermal heating and cooling technologies, it is imperative to pair demonstration and deployment activities with innovative outreach and engagement strategies that identify deployment pathways tailored to specific community needs.

The Geothermal Technologies Office (GTO) will play a critical role in realizing these advancements in support of fully achieving geothermal's status as America's next energy powerhouse.

1.2 The Geothermal Technologies Office's Vision, Mission, Strategic Goals, and Research Areas

GTO's vision is a vibrant domestic geothermal sector that contributes to a carbon pollution-free electric sector by 2035 and a net-zero emission economy by 2050 while providing economic opportunities and environmental benefits for all Americans. The GTO mission is to increase geothermal energy deployment through research, development, and demonstration (RD&D) of innovative technologies that enhance exploration and production.

GTO has outlined three Strategic Goals that serve as the basis of its research portfolio on the pathway to boost

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[1] Unpublished estimates from the National Renewable Energy Laboratory have shown deployment potential to exceed 120 GWe by 2050 under aggressive decarbonization pathways.

geothermal deployment. Achieving such deployment will increase the ability of geothermal to contribute affordable, low-carbon energy to Americans and create long-term, well-paying U.S. jobs.

Strategic Goal 1: Drive toward a carbon-free electricity grid by supplying 60 GW of enhanced geothermal systems (EGS) and hydrothermal resource deployment. Aggressive technology improvements in EGS and hydrothermal resources combined with reduced permitting and regulatory timelines will enable significant deployment of geothermal electric generation and will provide essential firm, flexible capacity to support a carbon pollution-free electric sector by 2035 and deliver a net-zero emission economy by 2050.

Strategic Goal 2: Decarbonize building heating and cooling loads by capturing the economic potential for 17,500 GDH systems and by installing GHPs in 28 million households nationwide. Widespread adoption of GDH and GHP technologies in residential and commercial buildings will require transformational improvements in the economic accessibility, federal, state, and local tax incentives; social acceptance; and permitting and regulatory timelines. Geothermal heating and cooling technologies provide a step-change in building efficiency, reduce peak heating and cooling loads, and reduce stress on the bulk power system to meet the Administration's goal to reduce the carbon footprint of the U.S. building stock by 80% by 2035 and deliver a net-zero economy by 2050.

Strategic Goal 3: Deliver economic, environmental, and social justice advancements through increased geothermal technology deployment. Geothermal technologies create clean energy jobs and generate substantial local economic activity, including wage spending, land-lease payments, property taxes, royalties, and other important cumulative expenditures. Geothermal energy addresses environmental and social justice issues because its high capacity factor, small physical footprint, and wide-ranging application ensure that it can be utilized in urban centers, rural areas, and remote communities. GTO will continue to document and amplify the benefits that geothermal can have for communities nationwide.

GTO will meet these three Strategic Goals through research, development, demonstration, and deployment in six Research Areas. This Multi-Year Program Plan (MYPP) lays out these Research Areas and the associated technical objectives (Table 1.1), which include five technical areas and one less technical technology-agnostic area (Geothermal Integration and Awareness). Progress in each area is critical to meeting the promise of geothermal energy in both the electric and heating and cooling sectors.

- **Exploration and Characterization:** The high costs and risks associated with geothermal exploration are a major barrier to expanded development of both conventional hydrothermal and EGS resources. This Research Area focuses on technology and cost improvements for geothermal resource characterization during early exploration phases, which will improve resource targeting for all geothermal resource types and holds significant potential to improve project economics. This Research Area intends to address challenges and barriers that include cost-prohibitive data collection, limited public data availability, and low subsurface spatial resolution of data in support of Strategic Goal 1.

- **Subsurface Accessibility:** Subsurface access through drilled and completed wells is required for all forms of geothermal energy exploration, characterization, and development. This Research Area encompasses efforts to reduce the time and cost associated with the drilling of geothermal wells, ultimately meeting the key objective of achieving the "ideal" drilling cost curves used in the *GeoVision* analysis Technology Improvement scenario. Efforts in this area include investments that enable tools and other hardware capabilities that are more resilient in the extreme environments associated with drilling and producing geothermal reservoirs. This research intends to meet the challenges and overcome the barriers around drilling in high-temperature, hard, fractured rock formations.

- **Subsurface Enhancement and Sustainability:** Achieving aggressive EGS and hydrothermal resource deployment will require improving sub-economic naturally occurring hydrothermal systems or developing fully engineered geothermal reservoirs. This geothermal energy recovery must be enhanced and sustained over project lifecycles in order to optimize geothermal energy, requiring significant RD&D efforts. This Research Area intends to meet the challenges and overcome the barriers to high reservoir stimulation technology costs and limitations to existing numerical models, ensuring enhanced and sustained geothermal energy.

- **Resource Maximization**: Geothermal resources contribute toward U.S. grid reliability, resilience, and security, supporting development of a robust domestic clean energy manufacturing supply chain, and providing effective alternatives to grid-dependent heating and cooling as well as energy storage solutions for the built environment. This Research Area intends to develop and deploy new technologies, capabilities, as well as operational activities that maximize geothermal resources while instilling geothermal value recognition across the spectrum of use cases.

- **Data, Modeling, and Analysis:** Data underpin RD&D conducted across all GTO MYPP Research Areas. Ensuring the quality and quantity of such data is critical to support effective data dissemination in DOE-developed technology and cost models, conduct strategic analyses that identify emerging GTO research opportunities, as well as tracking program-wide progress toward meeting metrics and goals. The Data, Modeling, and Analysis (DMA) area intends to build on these activities by providing critical support and enabling functions in data best practices, modeling, strategic analysis, and outreach and communication that advance all GTO MYPP Research Areas. For instance, DMA insights on added value streams for geothermal links directly to building out demonstration work in Resource Maximization.
- **Geothermal Integration and Awareness:** Each of GTO's subprograms focuses on a distinct aspect of geothermal energy and addresses challenges unique to those aspects; however, several additional GTO focus areas cut across multiple subprograms. This Research Area spans technology, workflow, commercialization, and stakeholder engagement activities that include using machine learning techniques in RD&D activities, incorporating advanced manufacturing innovations for geothermal technology development, and active support of geothermal technology commercialization, promotion of trust in federal government messaging and opportunities, and strategic socialization to operate across the United States. Additionally, integration of oil and gas infrastructure, workforce, and knowledge into the geothermal industry as well as broader geothermal community and engagement with key stakeholders, such as states and communities, on the benefits and myriad applications of geothermal energy will build awareness and support for geothermal development opportunities.

GTO has laid out performance goals for all technical Research Areas in Section 2, including the current comparable baseline and target year by which those goals are expected to be achieved.

Table 1.1. Summary of Geothermal Technologies Office Research Areas and Related Objectives

Research Area	Technical Objective
Exploration and Characterization	Improve resource targeting for all geothermal resource types
Subsurface Accessibility	Improve drilling costs toward 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 using data to identify and address barriers to geothermal deployment
Geothermal Integration and Awareness	Expand stakeholder education and outreach to improve understanding of geothermal energy and advance geothermal technologies

Geothermal resources span a range of temperatures, depths, and levels of technology readiness. Each of GTO's subprogram areas focuses on a distinct aspect of geothermal energy and has unique challenges; however, several of GTO's research activities cut across multiple subprogram areas. For instance, advances in drilling can be leveraged to help advance drilling for hydrothermal, low-temperature, and EGS. As such, GTO has outlined Research Areas that touch on common areas of focus across the four subprogram areas. Each Research Area has a distinct objective, the achievement of which is crucial to GTO's overall Strategic Goals (as illustrated in Table 1.2). Research Areas are summarized in Table 1.2 and are the basis for the technology plan (Section 2).

GTO's Strategic Goals directly feed GTO's vision, mission, objectives, and MYPP performance goals. These factors are at the core of GTO's activities and are summarized in Table 1.2.

<table>
<tr><th colspan="3">Table 1.2. Summary of Geothermal Technologies Office Vision, Mission, and Objectives</th></tr>
<tr><td colspan="3">GTO Vision
A vibrant domestic geothermal sector that addresses the climate crisis by contributing to a carbon pollution-free electric sector by 2035 and a net-zero emissions economy by 2050, and provides economic opportunities and environmental benefits for all Americans</td></tr>
<tr><td colspan="3">GTO Mission
To increase deployment of geothermal energy through research, development, and demonstration of innovative technologies that enhance exploration and production</td></tr>
<tr><td colspan="3">GTO's Activities Are Founded in the <i>GeoVision</i> Analysis Core Objectives
Increased access to geothermal resources | Reduced cost and improved economics for geothermal
Improved education and outreach about geothermal</td></tr>
<tr><th>Strategic Goals</th><th>Research Area Objectives to Achieve Goals</th><th>Performance Goals</th></tr>
<tr><td>Goal 1: Drive toward a carbon-free electricity grid by supplying 60 GW of EGS and hydrothermal resource deployment by 2050</td><td rowspan="3">Achieving the objectives in each Research Area (Section 2) is crucial to all three of GTO's Strategic Goals:
• Improve resource targeting for all geothermal resource types
• Improve drilling costs toward the "ideal" cost curves used in the <i>GeoVision</i> analysis
• Enhance and sustain geothermal energy recovery
• Accurately capture the value of geothermal energy resources
• Expand capabilities for using data to identify and address barriers to geothermal deployment
• Expand stakeholder engagement to improve understanding of geothermal energy and advance geothermal technologies</td><td rowspan="3">The MYPP includes 18 performance goals to measure progress and adjust research plans along the pathway.

Goals are generally planned for 1-, 3-, and 5-year targets.</td></tr>
<tr><td>Goal 2: Decarbonize building heating and cooling loads by capturing the economic potential for 17,500 geothermal district heating (GDH) installations and by installing geothermal heat pumps (GHPs) in 28 million households nationwide by 2050</td></tr>
<tr><td>Goal 3: Deliver economic, environmental, and social justice advancements through increased geothermal technology deployment</td></tr>
</table>

1.3 How the Geothermal Technologies Office Organizes Around Key Research and Deployment Focuses

GTO focuses on reducing geothermal development costs and risks by researching and advancing innovative technologies that address exploration and operational challenges; identifying and solving nontechnical barriers; and pursuing data collection to support technical and nontechnical work. GTO is organized into four subprograms, each of which funds research across the six Research Areas and contributes to the three Strategic Goals:

1. ***Enhanced Geothermal Systems.*** The focus of the EGS subprogram is to obtain understanding of basic and applied science challenges surrounding long-term subsurface heat flow, permeability enhancement, and stress evolution to support the development of replicable, sustainable heat exchangers. In the long term, strengthening the body of EGS knowledge through early-stage RD&D, field testing, and other innovative research will support industry to deploy the EGS levels calculated in the *GeoVision* analysis. GTO's EGS subprogram research addresses meeting the Government Performance and Results Act (GPRA) target of $0.06/kilowatt-hour by 2050 from newly developed EGS resources and will play an immense role in reaching the goal of a net-zero emission economy by 2050.[2]

2. ***Hydrothermal Resources.*** The GTO Hydrothermal Resources subprogram is focused on improving geothermal exploration, subsurface characterization, and drilling to reduce overall geothermal deployment costs. Key areas of focus include developing and demonstrating new exploration tools and technologies needed to capture the resource potential of undiscovered, "hidden" resources; assessing early-stage RD&D applications in machine learning for power plant operations; and advancing research in subsurface RD&D. Hydrothermal resources are well positioned to contribute to the goal of realizing a carbon-free electric grid by 2035.

3. ***Low Temperature and Coproduced Resources.*** The Low Temperature and Coproduced Resources subprogram conducts RD&D on technologies for geothermal resources below 300°F (150°C) as well as valuable critical materials extraction from geothermal brines and hybrid energy technologies that use geothermal in combination with other clean energy technologies. RD&D activities focus on improving the efficiency of low-temperature geothermal systems and expanding their utility through value-added commercial opportunities—facilitating near-term development of innovative geothermal technologies in geographically diverse areas of the country. The subprogram also researches the direct use of thermal resources for energy storage as well as process and space-heating applications, which have the potential to provide cost-effective, renewable thermal energy in large portions of the United States. Many activities under the Low Temperature and Coproduced Resources program focus on the added value of thermal energy, a major component of low-temperature geothermal. In addition to contributing toward the Administration's goal to reduce the carbon footprint of the U.S. building stock by 80% by 2035, low-temperature geothermal energy resources can be used by a wide array of community customers, including urban centers, rural areas, and remote communities.

4. ***Data, Modeling, and Analysis.*** GTO's DMA program works to identify and address barriers to geothermal adoption in the United States and validates and assesses technical progress across the geothermal sector. DMA analyses help to inform the direction and prioritization of GTO's RD&D. Work in DMA includes examining nontechnical barriers to geothermal deployment such as project permitting; modeling and validating the economics of geothermal technologies; collecting and disseminating data for stakeholder use; and assessing the environmental and economic effects of geothermal. DMA also helps develop and improve geothermal modeling tools and data sets, including supporting high-resolution geothermal resource assessments and the long-term maintenance, storage, and dissemination of critical data in the Geothermal Data Repository.[3]

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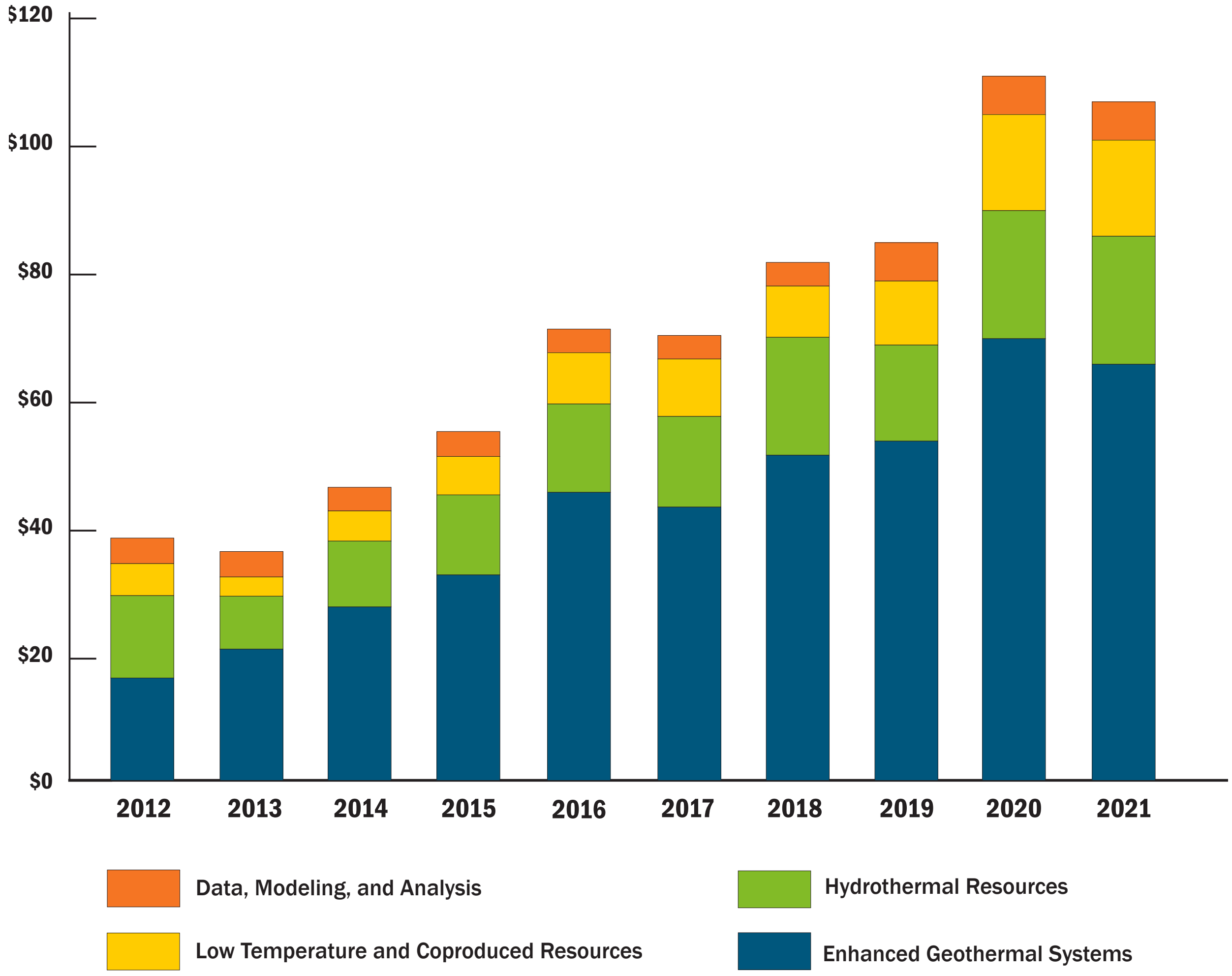
[2] https://www.govinfo.gov/content/pkg/BILLS-111hr2142enr/pdf/BILLS-111hr2142enr.pdf

[3] https://gdr.openei.org

Figure 1 illustrates annual budget appropriations (dollars in millions) for GTO's subprogram areas.

Figure 1. Geothermal Technologies Office Fiscal Year Appropriations (in $ millions)



2 Geothermal Technologies Office Technology Plan

The Geothermal Technologies Office Technology Plan highlights GTO's primary areas of research for FYs 2022–2026. As noted in the Executive Summary, the GTO research portfolio includes activities intended to contribute to progress toward the meeting the Office's three Strategic Goals. Sections 2.2–2.6 provide tables highlighting the contributions of respective GTO subprograms toward meeting GTO Strategic Goals, including distinct objectives and associated performance goals.

2.1 Exploration and Characterization

2.1.1 Introduction

The ability to cost effectively and rapidly characterize hydrothermal and EGS resources has a direct impact on their widespread deployment—which will support a clean, zero-carbon electricity grid and provide nationwide heating and cooling solutions. Technology improvements in exploration and characterization will lower project development timelines, costs, and risks, while increasing access to necessary capital—regardless of geothermal resource type (conventional identified or undiscovered hydrothermal resources, EGS resources, etc.), temperature (<150°C for direct-use applications and >150°C for power generation), or depth. Because financing carries costs (e.g., interest), technology and cost improvements for geothermal resource characterization during early exploration phases hold significant potential to improve project economics. As noted in the *GeoVision* analysis, the high costs and risks associated with geothermal exploration are major barriers to expanded development of the nation's undiscovered, or "hidden," hydrothermal resources and to realizing the economic and environmental benefits that could come with that expanded development. Similarly, successful development of EGS resources—which requires active engineering management throughout the life of the system—depends on resource characterization improvements even when a project is in operation.

The state of the art in resource characterization includes a variety of geological, geophysical, and geochemical tools and techniques that are costly to deploy at the desired levels of data collection and the respective development phases of interest. Publicly available data for areas with prospective geothermal resources are currently limited, placing additional barriers to entry for potential exploration and development companies and restricting geothermal resource discovery and deployment. No singular non-invasive (non-drilling) characterization method provides resolution on the spatial distribution of subsurface permeability, temperature, fluid, chemistry, or stress sufficient to enable the high-confidence well targeting necessary for industry's desired drilling success rates. Applying machine learning and joint geophysical inversion techniques to enhanced and reduced-cost data collection holds promise to improve this resolution.

To address these challenges and barriers, GTO is developing exploration and resource characterization tools and techniques to create a lower-cost and reduced-risk development profile for the full spectrum of geothermal projects. The characterization technologies addressed in this section span the three "Gs"—geophysics (including remote sensing), geochemistry, and geology. The three Gs are used to assess geothermal resource potential as well as to identify temperature; permeability; and the presence of fluids, their chemistry, and the stress regime in which they exist before developers make capital-intensive drilling decisions. Such assessment is important for geothermal resources regardless of their development phase (i.e., exploration, development, or operations). The geothermal industry has indicated the need for investments to reduce exploration and characterization technology costs and improve spatial resolution of

Technical Objective

Improve resource targeting for all geothermal resource types

Challenges and Barriers

- **Cost-prohibitive data collection and limited public data availability:** constrained ability for prospective explorers, developers, and operators to reduce project risk and aggressively increase rates of resource discovery and deployment.
- **Low spatial resolution of temperature, permeability, fluid, chemistry, and stress distribution in the subsurface:** reduced ability to understand subsurface features without invasive drilling and testing

The Three Gs of Characterization Technologies

- Geophysics (including remote sensing)
- Geochemistry
- Geology

subsurface characteristics to provide high-level guidance on areas in geophysics, geochemistry, and geology where improvements are most likely to be impactful (DOE 2011, DOE 2019). GTO also recognizes the need for additional analysis to support detailed understanding of which specific combinations of geophysical, geological, or geochemical technology improvements can yield the most effective cost reductions (see Section 2.5.3.2).

In addition to the three Gs, the resource characterization technologies discussed here feature a fourth area called "cross-cutting," which includes RD&D initiatives leveraging a combination of the science and techniques in the three Gs. Industry best practice is that data acquired through existing and new characterization technologies be integrated into a conceptual model of a geothermal resource and that the model is continually updated and refined over the life of the system. Well-constructed, accurate models are powerful decision-making tools for geothermal resource management. Drilling technologies, another cross-cutting area relevant to all parts of the GTO portfolio enabling confirmation or access to geothermal resources, are discussed in Section 2.2.

Table 2.1 highlights GTO subprogram contributions in Exploration and Characterization RD&D toward meeting overall GTO program goals. The majority of the planned geophysics, geochemistry, geology, and crosscutting RD&D pathways will be through the EGS, Hydrothermal, and Low Temperature subprograms in direct support of Strategic Goals 1, 2, and 3. The DMA subprogram also enables research insights through secondary contributions to Goals 2 and 3.

Table 2.1. GTO Subprogram Contributions in Exploration and Characterization RD&D for Meeting GTO Strategic Goals

Exploration and Characterization	Enhanced Geothermal Systems	Hydrothermal Resources	Low-Temperature and Coproduced Resources	Data, Modeling, and Analysis
Goal 1: Drive toward a clean, carbon-free electricity grid 60 GW of EGS and hydrothermal resource deployment by 2050	Define site conditions needed for engineering an EGS reservoir	Discover hydrothermal systems (i.e., confluence of heat, water, and permeability)		
Goal 2: Decarbonize building heating and cooling loads by capturing the economic potential for 17,500 GDH installations and by installing GHPs in 28 million households nationwide by 2050	Define site conditions needed for engineering an EGS reservoir	▨	Resource assessments for geothermal heating and cooling	▨
Goal 3: Deliver economic, environmental, and social justice advancements through increased geothermal technology deployment	Sustainable development of geothermal resources will benefit environmental, economic, and social well-being of communities across the nation			▨

Green: GTO subprograms with primary Research Area contributions toward GTO Strategic Goals

Gray: GTO subprograms with secondary Research Area contributions toward GTO Strategic Goals

No fill: GTO subprograms with tertiary Research Area contributions toward GTO Strategic Goals

2.1.2 Highlighted Performance Goals

Table 2.2 outlines key GTO performance goals through FY 2026 for enhancing the ability to locate and characterize geothermal resources.

Table 2.2. Exploration and Characterization Highlighted Performance Goals

Activity/Objective	Mechanism	Target FY to Achieve	Baseline (current status)
Validate multi-physics inversion methods, high-fidelity models, and machine learning through well targeting	Test and validate inversion and 3D modeling methods by drilling, testing, and confirming well targets as part of DE-FOA-0002219.	FY 2023	While physics-based inversion methods have been used, they are limited in quantitative rigor and have not extensively incorporated machine learning models for improved well targeting.
Double the discovery rate for undiscovered (or "hidden") geothermal systems	Data being collected through ongoing PFA* and GeoDAWN** initiatives, along with other exploration RD&D initiatives under development, can be leveraged with machine learning techniques developed as part of DE-FOA-0001956 to improve the discovery rate of undiscovered hydrothermal systems	FY 2026	Paucity of new publicly available data limits commercial exploration and deployment, impacting the acceleration along an exploration learning curve. The current discovery rate is estimated at ~190 megawatts-electric/year (Augustine 2019).

** GTO's Play Fairway Analysis (see Section 2.1.3.4)*

*** GTO's Geoscience Data Acquisition for Western Nevada (see Section 2.1.3.1)*

2.1.3 Research and Development Pathways

2.1.3.1 Geophysics and Remote Sensing

As articulated in the *GeoVision* analysis, progress is needed in detecting subsurface signals to remotely identify and characterize underground attributes. Similar to the use of radiology in the medical field to assess the need for and improve the success rates of costly and invasive procedures, the geothermal industry would benefit from technology breakthroughs in non-invasive, lower-cost geophysical and remote-sensing technologies. A range of geophysical methods are available for geothermal characterization and investigation. Improvements in geophysical methods have sizeable potential impact because of their ability to image the subsurface prior to costly, risky, and invasive drilling.

Geophysical techniques are principally used to map subsurface structures that help identify and define geothermal systems, such as fracture networks, faults, lithologic changes, heat flux, the presence of fluids, and permeability boundaries. These subsurface features are mapped using reflections of acoustic (seismic) and electro-magnetic waves, variations in the local gravity and magnetic fields, and thermal gradients (Gasperikova and Cumming 2020). Remote-sensing techniques enable large-scale mapping of surface features—e.g., mineral, vegetation, and thermal properties—as identifiers of geothermal resources. There are two main types of remote sensing: passive and active. Passive sensors detect natural emitted and reflected radiation. Active remote sensing uses the reflected, or backscattered, signal from energy emitted at predetermined wavelengths. Satellite and airborne imagery can map zones of secondary mineral alteration associated with emerging geothermal fluids and attributes such as heat flux. Aerial photography and terrain mapping with laser ranging also illuminate surface structural features associated with geologic settings.

Geophysical models and geophysical and remote-sensing data are required to advance geothermal technologies, as are advancements in temperature-gradient and heat-flow measurement tools and processing methods. Other needs include improved techniques for measuring thermal conductivity in high-temperature environments and broader understanding of existing heat-flow measurement tools and their effect on the accuracy of geothermal system characterization. Advancements in seismic data interpretation, such as efficient waveform inversion techniques, will provide better interpretation of geothermal resources at resolutions required to support effective exploration, development, and operations decision making.

In addition to temperature gradient, heat-flow measurement technology, and seismic data interpretation, there is a need to improve airborne geophysical data. This need could be met by testing advanced airborne tools—including magnetotelluric and time-domain electromagnetic tools over known geothermal systems—or by leveraging other agencies' satellites and airborne data and combining multiple airborne sensors on a single platform.

Remote-sensing advancements are needed to enable the acquisition of high-resolution remote sensing data sets via multiple methods over large areas in new regions. Specific needs include establishing reliable automated processing tools and techniques and developing affordable software for subsurface data-set model integration. GTO will focus on innovations in geophysics and remote sensing that improve surface-based, subsurface, and *in-situ* measurement tools and techniques.

Improve subsurface/*in-situ* measurement tools and techniques. In general, geothermal developers need better and potentially new borehole tools for measuring the spatial distribution of subsurface permeability, temperature, fluid, chemistry, and stress. More widespread understanding and use of advanced and commercially available characterization tools will significantly improve the accuracy of geothermal system characterization. Use of some commercially available temperature measurement technologies is currently limited because the tools are not easily accessible or the techniques to analyze the data are cost prohibitive. Additionally, the stability of fiber-optic cables (a distributed temperature-sensing tool) can be problematic, especially under high temperatures. Some progress has been made, but current technology does not function within the temperature ranges required by the geothermal industry. GTO will focus on improving the commercial availability of existing reservoir characterization measurement technologies by conducting research to improve the stability of fiber-optic cables in high-temperature environments; conducting research on thermal properties of rocks, including thermal conductivity; and researching and developing easier and more cost-effective ways to measure properties at high spatial and temporal resolutions. This research may involve longer-term technology improvements and the development of new logging tools for thermal conductivity.

Improve surface-based geophysical and remote-sensing techniques. The geothermal industry will benefit from improved, next-generation geophysical surface and airborne-derived data. Advances in this technology area will help identify undiscovered, or "hidden," geothermal resources. Technical challenges include issues with flying surveys and interception in areas of high relief. There is also a need to improve other, non-invasive geophysical techniques and data collection critical for subsurface monitoring and characterization. Advances in ambient noise tomography, seismoelectric effects, geodetics, and the inversion of these and other innovative geophysical data sets will contribute significantly to attaining proficiency in characterizing where fluid exists in the subsurface and how it moves over the lifetime of a geothermal project. RD&D in this area will focus on improving and validating data collection tools (e.g., control source electromagnetic) and improving data processing techniques through advanced coupling processing techniques to better interpret geophysical signals, e.g., seismic reflection data in crystalline geological environments. Advances are needed to enable the acquisition of high-resolution remote sensing data sets via multiple methods over large areas in new regions. Additionally, there is a need to establish reliable automated processing tools and techniques and to develop affordable software for subsurface data-set model integration. Reducing the cost of these data collection activities through technology RD&D and leveraging federal dollars directly toward data acquisition activities in areas known to be prospective for geothermal resources are likely to be impactful activities that advance the state of the art for geothermal. For example, GTO intends to leverage interagency agreements in data collection and machine learning initiatives, such as the Geoscience Data Acquisition for Western Nevada (GeoDAWN), to make progress in these areas.

2.1.3.2 Geochemistry

Geochemical techniques provide information on fluid source, heat source, subsurface temperature, and local and regional fluid flow paths and histories. The chemical and isotopic compositions of fluids collected at the surface provide indications of subsurface temperatures using a variety of empirical and experimental water-rock-gas geothermometers. Fluid and heat sources can often be identified through characteristic isotopic signatures. Spatial changes in fluid chemistry and isotopic compositions reveal important information on the flow rates and paths of geothermal fluids through the system.

Geochemical and isotopic techniques for identifying fluid and heat sources in geothermal systems are well established. However, the geothermal industry lacks reliable tools for determining subsurface temperatures, fluid flow paths, and rates and for identifying potential surface manifestations of hidden systems. Chemical and isotopic geothermometers are based largely on empirical data, and interpretations of calculated temperatures for natural systems rely largely on experience. Next-generation geothermometers that incorporate chemical and isotopic thermodynamics of the water-rock-gas systems of interest need to be developed. These new tools will also provide an enhanced assessment of fluid flow histories, such as dilution, phase separation, flow rates, and flow paths. GTO will therefore focus its efforts on the RD&D of improved geochemical techniques to estimate reservoir temperatures, processes, fracture flow, and sustainability.

Improve techniques to estimate reservoir temperatures and processes. At conventional hydrothermal power generation temperatures (150°C and up, to the critical point of water [374°C]), RD&D is needed to validate the thermodynamic databases that underpin existing liquid, gas, and isotope geothermometry and fluid-rock equilibria. As with conventional hydrothermal systems, understanding and managing the chemical evolution of EGS systems will be essential to ensuring their resource sustainability.

At present, geothermometers largely reflect empirical correlations and are not specifically related to the range of lithologic and tectonic regimes, nor the range of solution compositions in which geothermal systems may be found. There is a need to validate existing thermodynamic data under different geothermal conditions. Geothermal reservoirs and hydraulically connected aquifers exist at a range of temperatures and depths, such that equilibrium fluid compositions can be overprinted by re-equilibration (sometimes multiple times). These signatures may still be present in fluids (water and gas) that are sampled at the surface and thus have a “memory” of a deeper reservoir condition. However, decoupling these processes is difficult with existing methods. New insights may be gained from principal component analysis and machine learning technologies, especially when coupled with other exploration data sets.

Beyond the critical point of water (374°C), existing thermodynamic data must generally be extrapolated; by definition, then, these data incorrectly describe equilibrium chemistry or kinetic rates of reaction within the systems of interest. Acquiring experimental data is necessary to (1) define the thermodynamics of mineral-supercritical fluid equilibria to conduct the coupled numerical modeling of these systems and (2) support the production and use of high-temperature and high energy-density geothermal resources.

2.1.3.3 Geology

Geologic techniques provide the historical and structural framework within which geophysical, geochemical, and remote-sensing data are interpreted. A geologic model that incorporates structural data with data from these three technical areas can be used as guidance for subsequent exploration, development, and operational strategies. Surveying and mapping local and regional geologic structures, lithologies, and past and present strain rates are the most common geological methods for identifying potential geothermal sites.

The geology field requires advances in stress and strain data mapping and in correlating improved tectonic stress and strain data with thermal data. Stress and strain maps would help predict fractures and assist in understanding subsurface permeability distribution. Advances could be made by acquiring additional data to address gaps in borehole, local structural, and regional geodetic data and by developing detailed district maps and 3D models of strain and stress. Overall, there is a need for improved conceptual models to understand the subsurface, which will in turn improve drilling success rates and reduce costs.

Map stress and strain data. Stress and strain data are currently sparse in most geographic areas. Some areas lack well-exposed strain indicators, whereas others lack detailed geologic mapping and/or borehole data. Advancing the state of the art will require continued support for quaternary fault studies and studies comparing borehole data to local fault kinematic data. Developing and publishing detailed district stress and strain maps that include stress inversions and modeling, slip tendency analysis, and induced seismicity estimates will improve understanding of the geologic context within which geothermal resources may be developed and placed into production. An additional area of focus is tools and techniques that provide insights of in situ stress directions and magnitudes and their variability throughout reservoirs. GTO will also support quaternary fault studies, which could be aided significantly by remote-sensing and airborne geophysical data collection as described in Section 2.1.3.1. This GTO support will lead to improved statistically based permeability determinations for well targeting and better understanding of induced seismicity for geothermal fields.

Conduct regional geologic mapping. GTO support to state and federal geological surveys to conduct regional-scale geologic mapping in prospective geothermal areas would provide essential, low-cost, and high-value data. Such data are critical to establishing the structural and lithologic context for both identified and undiscovered geothermal systems. In the United States, geologic mapping is conducted primarily through the U.S. Geological Survey's (USGS) STATEMAP component of the National Coop erative Geologic Mapping Program. According to the USGS website, the primary objective of STATEMAP is "to establish the geologic framework of areas determined to be vital to the economic, social, or scientific welfare of individual States."[4] The website also explains that STATEMAP mapping priorities are established by State Geological Surveys in consultation with a multi-representational State Mapping Advisory Committee, and state-level priorities may not necessarily prioritize regions that are highly prospective for geothermal resources. GTO can coordinate with the USGS Geothermal Resources Investigations Project to identify high-priority areas that require regional geologic mapping, which can then be elevated for priority acquisition through the STATEMAP program and potentially supported through interagency cooperation.

2.1.3.4 Cross-Cutting Initiatives and Technologies

Cross-cutting initiatives and technologies are those that involve some combination of science and the exploration and characterization techniques described in the preceding technology areas. The goal of cross-cutting technologies is to improve data interpretation by combining techniques to minimize the ambiguity of stand-alone data.

Opportunities exist for technical advancements that will provide cross-cutting support for all geothermal exploration and characterization technologies. Improved, multi-disciplinary conceptual models in prospective areas of undiscovered hydrothermal resources (as determined through GTO's Play Fairway Analysis [PFA]) hold promise for increasing understanding of the subsurface, thereby improving drilling success rates and project economics. Subsurface permeability can be better understood by developing and confirming a model that connects geophysics, hydro-geochemical data, and geologic data along with mapping permeable paths in the subsurface.

Opportunities also exist for developing projects to model fluid flow in the fractured crust. Research for this work can include 3D modeling techniques and software as well as improved and more user-friendly data integration tools and software for model development. Improvements in 2D and 3D data-inversion codes, especially of multiple data sets, offer opportunities to improve the imaging resolution of key subsurface features in geothermal environments. The application of stochastic or Monte Carlo inversions to match cross-disciplinary datasets can generate a range of possible models.

Extend Play Fairway Analysis and enhance multi-disciplinary models. GTO has funded RD&D to adapt the PFA technique from the oil and gas industry to the geothermal industry. PFA targets the identification of undiscovered or "hidden" hydrothermal systems by incorporating the regional or basin-wide distribution of known geologic factors that control the occurrence of a particular type of geothermal system. By conducting PFA in unexplored or underexplored regions or by using new play concepts in basins with known geothermal potential, GTO research quantified and reduced uncertainty in geothermal exploration. This effort focused on the resource potential of 30 GW_e of undiscovered hydrothermal resources that the USGS estimates exist in the United States. The successful PFA work yielded numerous favorable prospects, with the potential for further study to unlock that geothermal potential.

Significant additional work in developing new, multi-disciplinary conceptual models for geothermal play fairways remains and could contribute to exploring prospective geothermal play fairways in the Aleutians, Cascades, Hawaii, and Snake River Plain. Conceptual models are in various stages of development for these play fairways; in many cases these models have reached an exploration stage where some level of drilling is required, as in the case of recently undertaken GTO-supported demonstration projects in Nevada. If successful, such efforts can support additional demonstration projects that validate the play concepts. Through continued support to PFA, GTO will test and validate multi-physics inversion methods, 3D modeling techniques, machine learning approaches, and conceptual modeling through field-demonstration well targeting.

Develop 3D modeling techniques, software, and innovative data processing and analysis. Enhanced software will lead to better understanding of conceptual

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[4] https://www.usgs.gov/programs/nationalcooperative-geologic-mapping-program/science/statemap-0

models and improved numerical geothermal system models, in turn leading to improved resource management and reduced drilling costs. Currently, 3D software exists for imaging and mapping magnetotelluric data. While multiple software programs are available from various vendors, each software has its pros and cons. Academic institutions have developed 3D magnetotelluric inversion algorithms, but the code is not shared; by contrast, many academic groups offer open-source 3D microearthquake inversion packages. The high cost of these modeling techniques limits the commercial application of what is otherwise a proven technology.

Physics-based numerical modeling codes have improved substantially in the national laboratory space. Commercialization of those codes, however, has lagged. Practical adoption and application of fully coupled thermo-hydraulic-mechanical-chemical modeling codes in the geothermal industry has also been limited. Additionally, the commercial availability of full-field numerical modelling software that couples a physics-based numerical reservoir model to a surface network through a wellbore simulator is limited and a full-field model that couples thermo-hydraulic-mechanical-chemical codes is currently unavailable.

GTO support for 3D modeling software advancements will result in a greater ability to integrate complete datasets, use of a common platform enabling greater interoperability and easier exchange of information, lower cost, and better availability. GTO will support continued RD&D of high-fidelity, fully coupled, full-field numerical models in pursuit of commercializing a low-cost and user-friendly software package.

2.2 Subsurface Accessibility

2.2.1 Introduction

Subsurface access through drilled and completed wells is required for all forms of geothermal energy exploration, characterization, and development. The costs of accessing the reservoir are an important determinant of the economic viability of geothermal energy projects. Reducing those costs is paramount in achieving the geothermal energy potential across all uses of geothermal energy outlined in the *GeoVision* analysis and ultimately contributing to a net-zero emission economy by 2050.

Well construction in geothermal environments is often hampered by low drilling rates and, as such, the time it takes to construct a well. This is historically the case of wells drilled for geothermal electricity-generation projects. In the western United States, average daily drilling rates are commonly on the order of 150-250 ft/day, about an order of magnitude lower than rates associated with continental oil and gas development in shale rocks. The rock in western U.S. geothermal projects is hard, fractured, and abrasive, making it a challenge to use advanced fixed-cutter bits (i.e., those with polycrystalline diamond compact [PDC] cutters. Formations are also often underpressurized, with low formation fluid pressures; this leads to circulation loss during drilling and can cause additional costs in terms of flat time (i.e., non-productive time, material costs, and loss of drilling equipment). State-of-the-art drill rigs and associated higher daily rig rental costs are commonly eschewed due to the tight margins associated with many geothermal development projects.

Technical Objective

Improve drilling costs toward the "ideal" cost curves used in the *GeoVision* analysis

Challenges and Barriers

- **High-temperatures environments:** need for specialized materials and tool designs
- **Hard, fractured rock:** geothermal reservoir rock compressive strengths that are typically higher than those drilled in oil and gas, translating to lower drilling rates and increased costs
- **Lower overall resource value:** limited use of more advanced and costly technologies for subsurface access
- **Larger well diameters and more extensive well construction requirements:** drive requirements beyond other subsurface energy industries and result in higher well-development costs

Geothermal wells are commonly much larger in diameter than those drilled for oil and gas—often by a factor of more than two. While slow drilling rates of geothermal wells contribute to their high cost relative to oil and gas wells, the cost of steel and cement associated with larger geothermal well diameters is also a major contributor to the high costs of geothermal wells. These materials (primarily casing and cement) are emplaced during geothermal well construction and account for as much as 50% of the cost of a geothermal well (Lowry et al. 2019).

Enabling technologies—from electronics to elastomers that can survive harsh conditions—are fundamental to addressing the environment associated with geothermal drilling. Technologies that perform in high-temperature, high-pressure, high-shock, corrosive environments are required for a wide range of downhole tools needed for drilling, logging, and monitoring of geothermal wells. Additionally, consumables such as lost-circulation materials are ripe for improvement in geothermal conditions. Developing these base technologies will enable the building of systems needed to construct and operate geothermal wells.

GTO has and will continue to pursue efforts to reduce the time and cost associated with the drilling of geothermal wells. Efforts in this area will continue to include investments in base technologies that enable developing tools that are more resilient in the extreme environments associated with accessing geothermal reservoirs.

Table 2.3 highlights GTO subprogram contributions in Subsurface Accessibility RD&D toward meeting overall GTO program goals. The majority of the planned RD&D on drilling time, well components, and enabling technologies will be through the EGS, Hydrothermal, and Low Temperature subprograms in support of Strategic Goals 1, 2, and 3. The DMA subprogram also enables research insights through secondary contributions to all Strategic Goals.

Table 2.3. GTO Subprogram Contributions in Subsurface Accessibility RD&D for Meeting GTO Strategic Goals

Subsurface Accessibility	Enhanced Geothermal Systems	Hydrothermal Resources	Low-Temperature and Coproduced Resources	Data, Modeling, and Analysis
Goal 1: Drive toward a clean, carbon-free electricity grid 60 GW of EGS and hydrothermal resource deployment by 2050	Lower drilling costs through adaptation of existing and development of new technologies			▨
Goal 2: Decarbonize building heating and cooling loads by capturing the economic potential for 17,500 GDH installations and by installing GHPs in 28 million households nationwide by 2050	Lower project risk through lower drilling costs using existing technology and development of new technologies			▨
Goal 3: Deliver economic, environmental, and social justice advancements through increased geothermal technology deployment	Lower environmental impact drilling systems / employing workers in every American community / wells cannot be outsourced			▨

Green: GTO subprograms with primary Research Area contributions toward GTO Strategic Goals

Gray: GTO subprograms with secondary Research Area contributions toward GTO Strategic Goals

No fill: GTO subprograms with tertiary Research Area contributions toward GTO Strategic Goals

2.2.2 Highlighted Performance Goals

Table 2.4 outlines key GTO performance goals through FY 2026 for enabling better drilling and completion of geothermal wells.

Table 2.4. Subsurface Accessibility Highlighted Performance Goals

Activity/Objective	Mechanism	Target FY to Achieve	Baseline (current status)
Implement a drilling data acquisition and sharing platform for DOE-funded drilling efforts and engage with industry and international partners to implement sharing across the industry	All awards involving well development will include data acquisition requirements. Lab direct funded included on data sharing platform leveraging the Geothermal Data Repository.	FY 2023	Availability of drilling data, public and private, is limited and commonly accepted platforms for acquiring and sharing these data, particularly high rate digital data, have not been implemented.
Implement data-driven practices in all DOE-funded drilling activities that will allow more efficient rock reduction toward doubling the national daily average rate of penetration	Data acquisition requirement provides the foundation for data driven drilling practices. Leverage the results of DE-FOA-0001880 and recent demonstrations to guide deterministic and machine learning data-driven practices for awardees.	FY 2024	The current drilling rate for geothermal wells is on the order of 125–150 feet per day. Existing GTO research is advancing this space, but additional work is needed.
Evaluate advances and continue research in lost circulation control practices and material toward doubling the national daily average rate of penetration	Evaluate learnings from DE-FOA-0002083 and implement drilling demonstrations that incorporate these learnings and adaption of existing technologies to geothermal	FY 2024	The current drilling rate for geothermal wells is on the order of 125–150 feet per day. Existing GTO research is advancing this space, but additional work is needed.
Implement a program directed at reducing inground materials costs (casing and cement)	Develop a technology and execution roadmap addressing materials/ manufacturing methods to address critical issues.	FY 2026	Casing and cement can account for as much as 50% of the cost to construct a geothermal well. Reducing these costs is imperative to reducing well-construction costs.

2.2.3 Research and Development Pathways

2.2.3.1 Drilling Time

The costs associated with well construction are largely dependent on the time required to complete a well and the cost of materials used in construction. Geothermal well-advancement rates are generally slow, so one aspect to reducing costs is reducing the time required. Reducing the time it takes to complete a well to depth can have a substantive effect on the cost of drilling a well, particularly with drilling rates as low as they are for geothermal wells; doubling the average daily drilling rate can have a 10–15% savings on the total cost of a geothermal well. Improving drilling time is a challenge, however, because of difficult drilling conditions and an environment in which the advanced technologies used by other industries are either not available or are too expensive to justify under current geothermal economic conditions. Addressing drilling time requires RD&D in two intricately linked areas: improving the hole advancement rate (rock reduction) and reducing flat time (i.e., the time during which the hole is not being advanced).

Improve rock reduction rate. Currently, most geothermal wells are drilled with hard-rock roller bits—the workhorse of the drilling industry for nearly a century. However, in the 1970s, a synthetic diamond-cutting structure, known as PDC, was invented, with ready application to drill bits. As PDC bit performance has improved, the adoption of PDC bits in the drilling industry has been steady. In fact, PDC bits are now the mainstay of the oil and gas drilling industry because of the higher drilling rate and longer life they exhibit relative to roller bits. While GTO was an early and significant sponsor of RD&D related to PDC drill bits, the geothermal industry has generally not borne the fruits of these advances because of the nature of the rock and temperatures associated with geothermal environments. In general, geothermal reservoir rocks are stronger (harder) and more fractured that those found in oil and gas reservoirs. However, with improvements in these bits and evidence that they can provide a step-change in performance (Hackett et al. 2020), renewed and vigorous efforts to test and deploy advanced drilling structures are justified in geothermal environments.

In addition to fixed-cutter PDC bits, percussive drilling also offers rock reduction rates well in excess of that obtainable from roller bits, particularly in hard-rock environments. There are aspects of "hammer drilling" that were traditionally not compatible with geothermal environments, but advances in GTO-sponsored research in air-driven hammers and commercial advances in water-driven hammers offer opportunities to leverage those capabilities to improve rock-reduction rates for geothermal drilling.

The drill bit is just one portion of the bottomhole assembly, i.e., all the drilling tools that sit below the primary drill string. Bottomhole assembly components comprise motors, steering systems, logging-while-drilling/measurement-while-drilling tools, shock subs, and other tools. These tools are used to improve drilling performance and reduce flat time, and many incorporate seals and electronic and power components that limit the temperature environments in which they can operate. There are limited options for geothermal drilling using a subset of the tools available to the oil and gas industry but for sustained operation at temperature above 150–175°C. Additionally, some potentially useful tools are not compatible with larger-diameter geothermal wells. Opportunities to adapt, modify, or develop geothermal-compatible bottomhole assembly components should be investigated.

Geothermal industry access to advanced, modern drill rigs is limited due to tight margins associated with the low-value resource (compared to hydrocarbon). GTO will seek opportunities to support limited trials with more advanced and modern systems to determine if better and more costly equipment could result in lower overall project costs. Such testing would also better identify the "limiters" in performance that need to be overcome to drive down costs, particularly related to time. An early indicator of the promise in investing further in these opportunities was demonstrated at the Frontier Observatory for Research in Geothermal Energy (FORGE) in late 2020 through the use of a data-driven "physics-based limiter redesign workflow," coupled with training of all personnel in use of this workflow and the use of PDC bits that reduced anticipated drilling time for the first-of-its-kind highly deviated well in granite by more than half.

Improve decision making while drilling. Equally important to RD&D directed at adopting modern rock-reduction technologies is RD&D to improve the decision-making process during drilling. The use of digitally acquired surface and downhole drilling data to diagnose drilling performance is used throughout the oil and gas industry but has seen little adoption in the U.S. geothermal industry—yet this physics-driven approach to drilling control has been shown to have a major influence on drilling performance. This approach begins with acquiring and acting on the mechanical specific energy (MSE) associated with the drilling process, i.e., the measure of the energy required to remove a unit volume of rock. Dupriest (2011) demonstrated a 40% improvement in average hole-advancement rates by making decisions based on MSE. Adopting a workflow that incorporates decision-making digital data in geothermal drilling is important and is necessary to advance the use of PDC bits. The use of MSE data to control drilling not only improves instantaneous drilling rates, but also reduces flat time caused by minimizing energy that is not directed at breaking rock (e.g., deleterious vibrations that cause tool failure). GTO will pursue RD&D directed at adopting and modifying this workflow in geothermal drilling operations.

Manage lost circulation and drilling fluid. Lost circulation, where fluids are lost to the formation during drilling, remains a critical issue in geothermal development due to the fractures and often underpressurized environments present in the subsurface. Lost circulation is a major cause of flat time (specifically non-productive time) associated with geothermal wells and can lead to wellbore damage, well control issues, and potential environmental impact. As such, GTO will necessarily continue technology development aimed to address lost-circulation prediction and control.

The design and management of drilling fluids can have a dramatic effect on the overall rate of penetration, and—other than mud weight drilling fluids—are often an afterthought in the design and execution of geothermal well construction projects. Drilling fluids are vital; they assist in lost circulation control, cool and clean the bit while drilling, lubricate the drill string, maintain stability of the wellbore, control formation fluid pressures, carry rock cuttings to the surface, and transmit hydraulic horsepower for driving downhole motors and other tools in the bottomhole assembly. There is a need for advances to support design of drilling fluid for geothermal applications and development of high-temperature additives, particularly those supporting lost circulation control. Additionally, advanced fluid management systems (e.g., managed pressure drilling) could play a role in improving hole advancement rates and reducing drilling time.

Improve casing and cementing. The time involved in casing and cementing wells has a dramatic effect on the overall rate in which a well is drilled. There are no obvious solutions to this issue, as it plagues all drilling operations. While additional training is always useful in gaining efficiencies, RD&D is warranted to conduct evaluations of options to reduce casing and cementing time—either through time-saving options such as casing while drilling or through methods to reduce the number of casing strings used to develop a typical geothermal well. Developing partnerships, such as with DOE's Advanced Manufacturing Office and Office of Science, could bolster RD&D to reduce casing and cementing time. Linked to this effort, particularly for highly deviated wells, is understanding the condition of the well before running casing. Gauge wells with limited tortuosity and doglegs reduce the problems and costs of casing and cementing, ensuring the drilling process is efficient reduces problematic wellbore conditions.

2.2.3.2 Well Components

The primary component costs for geothermal wells are casing and cement. While bit and drilling fluid costs are also important, reducing the costs associated with the casing and cementing of geothermal wells is paramount to reducing costs of geothermal wells. Actual costs are well dependent, but materials and services associated with casing and cementing can be as high as 50% of the well cost.

Reduce casing costs. Geothermal well casing is fabricated from steel, nickel, or titanium alloys, with steel being the predominant material. Since commodity prices drive the cost of these materials, options to reduce these costs should focus on the use of alternative materials as well as the use of less material in the casing of geothermal wells. Research into reducing material use should investigate leaner casing designs that result in safe, long-term well operations; leaner casing designs would have the advantage of less material as well as less flat time associated with casing and cementing activities. While a less likely solution in the near term, alternative casing materials (or casing fabrication methods) deserve attention given recent developments in advanced manufacturing.

Reduce cement costs. Cement is the primary fluid and chemical barrier between reservoir rock and the cased portion of the well. The short- and long-term integrity of the cement are both imperative for sustained well performance. Reducing the cost of cement materials in geothermal well construction can follow a similar path to that of reducing casing; that is, using less material, developing alternative approaches, and investigating leaner casing designs. Using fewer casing strings or decreasing the annular space between the casing and the rock (e.g., through the use of expandable casing) would reduce well cost. Ordinary Portland Cement (OPC) is the most common cement used in geothermal wells. GTO's work on chemical resistant, high-temperature, self-healing cements should continue, with a focus on developing tailored cement chemistries that are practically deployable and can be sourced at costs comparable to or less than current OPC solutions. Alternatives to existing cementing materials are discussed in Section 2.2.3.3.

2.2.3.3 Enabling Technologies

Advancements in enabling technologies are necessary to adapt oil and gas methods and tools to geothermal well construction. Such advances are also the foundation to the development of systems that will lower materials costs in geothermal wells. The potential technology space is broad but can generally be divided between materials and electronics.

Research materials and manufacturing method enhancements. Materials commonly used in geothermal well construction are broad and include items such as elastomers for seals, packers, and motors; metals used in casing and drilling tools; organic and inorganic components in cements; solders; and bearings materials and lubricants. These materials have commonalities in their performance limitations within the high-temperature and harsh conditions of geothermal wells and the costs and availability of suitable materials for those conditions. Efforts to overcome these challenges should focus on improving materials that form key components that do not presently perform adequately in geothermal environments and reducing the costs of materials that do perform (without sacrificing that performance). Three areas that should be prioritized: elastomers, lower-cost and high-performance casing, and lower-cost and high-performance cement.

Elastomers degrade at varying rates, depending on the environment to which they are exposed and the length of exposure. Continued improvement of elastomers or alternatives to the organic elastomers used today is an important enabling technology that will support the development of everything from high-temperature drilling tools to casing and test packers used in drilling operations.

As noted, casing is a significant part of the cost of geothermal wells. Researching effective but lower-cost methods to produce and/or deploy this necessary well-construction component is important. RD&D is needed to explore alternatives to existing materials and alternative manufacturing methods that could reduce the amount of casing material needed or the method in which casing is deployed.

Research to develop cementing materials and additives that will provide the performance needed in a geothermal environment should continue. However, methods and technologies that could alter the traditional geothermal well cementing paradigm should not be ignored (e.g., robust designs that do not require fully cemented casing, converting drilling fluid into cement, eliminating cement with a swellable coating on casing). Such research offers long-term opportunity, but the cost associated with cement (and casing) justifies investment into future, robust, lower-cost solutions.

Conduct high-temperature electronics research. Electronics used in drilling and logging wells and for long-term monitoring of well performance are limited in geothermal applications. The availability of electronics for long-term operation above 225°C is also limited. A broader suite of components is needed to expand drilling-related systems and tools required for extended operations in high-temperature geothermal environments. Two basic approaches are needed. The first is to review existing components that are not rated at the requisite operating temperature but may be qualified through testing. It is not uncommon for some components to be underrated by the manufacturer; a method to qualify and publish results of available components has been shown to be a viable way to bolster the components available to tool builders. The second (and more costly) path is to initiate RD&D to build critical components. Among the critical components are processors, multi-chip modules, higher-bit A/D converters, field-programmable gate arrays/electrically erasable programmable read-only memory, failsafe capacitors, oscillators, large memory arrays, and batteries.

2.3 Subsurface Enhancement and Sustainability

2.3.1 Introduction

The heat resource in the United States is vast and greatly exceeds geothermal systems that can currently be used economically through targeted drilling and subsequent production of hot fluids for power generation or direct use. Growing geothermal electricity generation to 60 GW_e by 2050, as outlined in the *GeoVision* analysis, will require developing these heat resources by improving sub-economic naturally occurring hydrothermal systems or developing fully engineered geothermal reservoirs.

The science and engineering knowledge and technology base must be improved to better understand and predict how a reservoir will respond and evolve when subjected to operations that modify the permeability of the reservoir. Numerical tools exist to support these efforts; however, the subsurface is a complex, heterogeneous, and anisotropic environment, and refinement of these tools is a continuous effort. The complexity is amplified by the coupled nature of physical processes where stress, temperature, hydrology, chemistry, and biology can have marked impacts on system response during efforts to improve heat exchange and long-term operation. Data from laboratory, intermediate, and full-scale testing have been illuminating in supporting development of methods to predict reservoir response; as more data become available, the ability to predict reservoir response will continue to improve.

Technologies to develop and manage an enhanced reservoir are common in the oil and gas industry, but systems and knowledge to support analogous operations in geothermal environments are lacking. Developing these systems and knowledge is essential to successful EGS deployment, including greenfield EGS project development as well as near-field EGS efforts directed at capacity expansion of operating hydrothermal fields. For example, methods to enhance geothermal reservoirs through hydraulic stimulation have largely eschewed zonal isolation technologies, where select sections of the wellbore are isolated from the remainder of the well due to the limited availability and cost of suitable systems. However, it is now understood that targeted zonal isolation will facilitate purposeful enhancement approaches and is required for the development of EGS. In addition to zonal isolation, technologies and techniques for enhancement are often not applied consistently in geothermal environments. Hydraulic and chemical stimulation methods have been used in the past; however, sequences of stimulation operations, pumping rates, and pumped volumes of fluids are, at best, subjective. The chemistry of stimulation fluids and their coupled interaction with the reservoir is a known issue, but the ability to exploit potential benefits and mitigate adverse effects has not been developed to allow engineering control of the operation. Alternative methods such as the use of energetic systems to supplement traditional hydraulic stimulations may have promise but are not adequately understood in a geothermal context. Flow control—other than the running of casing and liners—is almost nonexistent in geothermal production; for greenfield EGS, however, some type of active or passive flow control system will be required.

The ability to characterize the reservoir during operations is key to understanding reservoir performance and, subsequently, the ability to intervene and modify reservoir response. The use of microseismic monitoring to characterize the results of reservoir enhancement operations was pioneered by the Energy Research and Development Administration (which later merged with the Federal Energy Administration to form the DOE organization, including GTO) and remains the primary method for monitoring the evolving permeability (fracturing) in the subsurface. Microseismicity monitoring is not only useful in characterizing the reservoir, but is an essential component to ensuring that reservoir enhancement operations are not a hazard or a nuisance to the public. Other monitoring activities such

Technical Objective

Enhance and sustain geothermal energy recovery

Challenges and Barriers

- **High technology costs:** limited existing deployable technology potential
- **Numerical modeling limitations:** limited ability to adequately couple multi-physics to simulate subsurface enhancement activities
- **Lack of subsurface capabilities:** limited ability to manipulate the subsurface and control physical changes
- **Low-resolution scales to characterize the physical state of the reservoir over operational lifetimes:** limited resolution and understanding, with unacceptable levels of uncertainty

as ground deformation (e.g., GPS and InSAR) and tracer studies—as well as surface and downhole measurements of production and injection well-flow rates, pressure, temperature, and chemistry—all provide key data whose availability are of great utility to operators. Timely data are critical to the ability to respond to changing reservoir conditions.

At least for the near future, microseismic monitoring will be the primary method to track evolving reservoir conditions. The capability of microseismic monitoring has progressed and improved over the last several decades, and the infusion of fiber-optic methods and high bandwidth digital geophones and accelerometers have improved capabilities. Additional areas for improvement remain, both in terms of sensor capability (namely temperature hardening and sensor placement) and the ability to reduce and interpret the data in near real time. Complementary monitoring systems that provide more direct measurements of fluid flow exist (e.g., tracers and electro-magnetic geophysical tools) but improvements that provide timely, continuous, and real-time data at actionable resolution continues to be a need.

GTO has performed RD&D across the spectrum of subsurface enhancement and sustainability, with significant progress made over the last few decades. Challenges remain, however, and it is important to pursue focused efforts to improve scientific understanding, the tools needed for enhancement, and the ability to understand reservoir evolution.

Geothermal and Microseismicity

To ensure that any seismicity associated with EGS development is not a hazard or a nuisance to the public, the DOE has developed *Best Practices for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems (EGS)*. This document provides a comprehensive methodology to ensure that hazards and associated risks of reservoir stimulation required for enhancement are understood and mitigated with complete transparency with all stakeholders and is used to ensure safe and successful project planning and execution at sites like FORGE.

Table 2.5 highlights GTO subprogram contributions in Subsurface Enhancement and Sustainability RD&D toward meeting overall GTO program goals. The majority of the planned RD&D on reservoir response, reservoir development and management, and reservoir characterization and monitoring will be through the EGS, Hydrothermal, and Low Temperature subprograms. The RD&D in this Research Area as applied to EGS will directly achieve all three Strategic Goals, while as applied to the Hydrothermal and Low Temperature subprograms will directly achieve Goals 2 and 3 only. The DMA subprogram also enables research insights through secondary contributions to all Strategic Goals

Table 2.5. GTO Subprogram Contributions in Subsurface Enhancement and Sustainability RD&D for Meeting GTO Strategic Goals

Subsurface Enhancement And Sustainability	Enhanced Geothermal Systems	Hydrothermal Resources	Low-Temperature and Coproduced Resources	Data, Modeling, and Analysis
Goal 1: Drive toward a clean, carbon-free electricity grid 60 GW of EGS and hydrothermal resource deployment by 2050	Refine predictive capabilities and develop stimulation and characterization technologies to enable commercial EGS			▨
Goal 2: Decarbonize building heating and cooling loads by capturing the economic potential for 17,500 GDH installations and by installing GHPs in 28 million households nationwide by 2050	Refine predictive capabilities and develop/refine stimulation and characterization technologies to enable commercial EGS for direct use	Refine predictive capabilities and develop/refine characterization technologies to monitor reservoir performance more effectively and optimize resource potential	Refine predictive capabilities and develop/refine stimulation and characterization technologies to expand direct use of geothermal heat and efficient GHP system design	▨
Goal 3: Deliver economic, environmental, and social justice advancements through increased geothermal technology deployment	Sustainable development of geothermal resources will benefit environmental, economic, and social well-being of communities across the nation			▨

Green: GTO subprograms with primary Research Area contributions toward GTO Strategic Goals

Gray: GTO subprograms with secondary Research Area contributions toward GTO Strategic Goals

No fill: GTO subprograms with tertiary Research Area contributions toward GTO Strategic Goals

2.3.2 Highlighted Performance Goals

Table 2.6 outlines key GTO performance goals through FY 2026 to support the ability to characterize and sustain geothermal reservoirs.

Table 2.6. Subsurface Enhancement and Sustainability Highlighted Performance Goals

Activity/Objective	Mechanism	Target FY to Achieve	Baseline (current status)
Collect, archive, and distribute high-fidelity multiphysics data associated with stimulations of in-field, near-field, and greenfield EGS reservoirs in crystalline rock at depth	FORGE (DE-FOA-0000890) and Wells of Opportunity (WOO) (DE-FOA-0002227) collect, archive, and distribute data associated with stimulations in greenfield and proximal to existing geothermal systems	FY 2022	Numerous EGS stimulations have been conducted worldwide, and data associated with many of these stimulations exist. However, this effort will provide a breadth of data not previously available to the broader research community. These data will further the understanding of rock mass response to stimulation in various geologic environments.
Increase the net production potential in an existing geothermal plant using advanced, targeted stimulation technologies in existing but sub-commercial wells	WOO Amplify FOAs (DE-FOA-0002227 and DE-FOA-0002525) are directed at using advanced stimulation technologies in the increase the production of existing geothermal plants	FY 2023	Past DOE-sponsored projects and commercial operations have shown that power production can be increased through reinjection of produced waters. However, these injections are largely untargeted and do not employ techniques that target specific sections of the well most suitable for stimulation.
Develop and test a prototype zonal isolation system to support stimulation, injection, and/or production in >7” diameter holes, at temperatures exceeding 225°C, for extended periods of time (>1 year)	Review the results of the Zonal Isolation FOA (DE-FOA-0001945) and seek demonstrations of the developed technologies. Through FORGE RD&D, develop and demonstrate advanced well completion technologies that incorporate zonal isolation technologies similar to those used in parallel industries	FY 2025	Various systems exist for zonal isolation in the oil and gas industry, but these technologies need to be adapted or redesigned to perform in geothermal conditions. Materials development at the system-component level may also be necessary.
Refine and optimize stimulation procedures using zonal isolation for reservoir enhancement in crystalline basement rock	Through FORGE (DE-FOA-0000890) and WOO (DE-FOA-0002227) execute full scale stimulation programs, monitor the effects, and refine subsequent stimulation procedures.	FY 2026	Limited options exist for zonal isolation in reservoir stimulation at geothermal conditions; the most common is open-hole stimulation.

2.3.3 Research and Development Pathways

2.3.3.1 Reservoir Response

An essential component in enhancing and sustaining a geothermal resource is the ability to predict the response of the reservoir to operations in the subsurface. Predicting the response of any system to disturbances requires a model of the system and data to support model development and validation.

Better predict response through laboratory and field testing and observations. The ability to predict reservoir response to enhancement operations (e.g., hydraulic stimulation) and evolution during production is required to effectively design and implement intervention strategies in support of EGS, hydrothermal, and low-temperature reservoirs. Both naturally formed and human-engineered geothermal reservoirs will evolve in response to the perturbations to which they are subjected, from putting drilled wells into production to full-scale stimulations in greenfield EGS projects. Better predicting reservoir response is an important RD&D need and will require testing at full scale with detailed characterization and monitoring to test and validate model capability.

Improve coupling of numerical/analytical modeling and validation. GTO has made significant investments developing analytical and numerical codes for predicting geothermal reservoir evolution. The next need is to develop data to validate these codes and refine constitutive models that represent physical processes in these codes. As noted, thermal, hydrological, mechanical, and chemical (and sometimes biological) processes in the subsurface are complex and highly interdependent. The ability to predict these coupled processes can be derived through assessment and analysis. Related data needs are best defined by integrating experimental activities with the modeling community and at scales ranging from laboratory to full-scale field. GTO research will seek to improve predictive capabilities through integrated testing and simulation, in turn enhancing the ability to predict and constrain reservoir response in difficult environments.

2.3.3.2 Reservoir Development and Management

Enhancing and operating a geothermal reservoir requires developing technologies and techniques to allow targeted operations that control locations within a wellbore for stimulation activities as well as zones where fluids are injected and withdrawn. In addition to targeted stimulations and flow control within wells, managing geochemical interactions, particularly scale formation in the subsurface and surface equipment, is required for long-term operations.

Investigate advances in stimulation technologies and techniques. Enabling technologies for geothermal reservoir enhancement are required for EGS development. These technologies may necessitate new well designs and completion schemes, new tools, injectate chemistries and materials, pumping schedules, and other changes. Advancing stimulation technologies and techniques is a major hurdle in advancing geothermal development toward the potential 60 GW_e of geothermal electricity-generation capacity and 320 gigawatts-thermal (GW_{th}) of economic district-heating potential outlined in the *GeoVision* analysis. Relative to the oil and gas industry, the geothermal space is very small and opportunities to advance stimulation technologies through trial and error are not realistic. Modeling and simulation supported by laboratory and field testing (Section 2.4.3.1) will play a vital role in identifying promising technologies and techniques for reservoir stimulation. Replicability of stimulation methodologies across all potential environments is not likely but finding approaches to identify the stimulation methodologies appropriate to the environment is a reasonable and achievable goal. Modeling and simulation will support this goal but modeling alone will not advance this capability; innovation in stimulation methods is also needed.

These advances will also require improvements in rock-mass characterization before, during, and following reservoir enhancement operations. A holistic approach that includes modeling and simulation to support developing advanced technologies and techniques is vital to find adaptable reservoir-stimulation technologies and techniques.

A crucial issue that must be addressed for long-term geothermal operations is the ability to engineer solutions to control mineral scale in the well, reservoir, and surface equipment. Scaling issues in the subsurface are largely dependent on the chemical make-up of injected fluids and the minerology of the reservoir rocks. Testing and reservoir models that incorporate chemistry (thermo-hydraulic-mechanical-chemical models) will be vital to understanding and controlling scaling in the subsurface. Amorphous-silica deposition in surface equipment and injection wells remains a broad issue, particularly in geothermal systems operating above 200°C. Efforts to better define the kinetics and hydrodynamics of silica scaling will be essential to developing engineered controls.

Assess and test zonal isolation and downhole flow control. Efforts to employ open-hole stimulation approaches have thus far had limited success.

Investigations over the last decade have confirmed that a robust approach to reservoir enhancement and sustained operations will require the ability to both isolate zones with the subject wellbores during stimulation activities and to control the flow into and out of the isolated sections of the wellbore. There are a range of technologies that support these operations in the oil and gas industry, but temperature limitations and wellbore diameters severely limit the application of these technologies in geothermal environments. Developing zonal-isolation and flow-control technologies is imperative to EGS, and advances in these technologies will provide useful reservoir-control options not currently available to the developers of conventional hydrothermal geothermal systems. Advancements in these critical technologies is a priority.

2.3.3.3 Reservoir Characterization and Monitoring

Reservoirs evolve over time, and understanding this evolution requires acquiring and assessing site data across all phases of development and operations. The ability to respond to reservoir changes requires that these data be processed and analyzed in a manner that is useful and timely; as data volumes expand, this need is particularly critical. Tools and sensors have advanced, but enhancing measurement capabilities and implementation methods is critical to characterize and monitor geothermal reservoirs.

Conduct real-time data collection, analysis, and response. Understanding geothermal reservoir behavior prior to, during, and after development activities is critical to ensure that reservoir enhancement efforts are implemented effectually. Effective characterization and monitoring help minimize capital and operational risks associated with drilling and stimulation of deep wells and are essential to monitoring reservoir performance and evolution over time. Interrogation methods, systems, and technologies must be tailored to the operational needs of geothermal reservoir; however, the utility of these data is dependent on the ability to assess and act in a timely manner.

Implementing advanced data processing and data analytics is necessary to allow timely responses to characterization and monitoring activities. This includes the integration of orthogonal data sources (e.g., microseismic and EM signals) where real-time integration and fusion of data is currently problematic. These needs are particularly important for reservoir stimulation where the ability to adjust operations in response to real-time monitored data is limited and yet critical for successful reservoir enhancement; it is also imperative for monitoring seismic hazards. As the data volume expands (e.g., distributed acoustic sensing), the need for rapid acquisition and analysis is becoming increasingly important and RD&D to ensure that collected data is useful to operational activities is required.

Develop advanced monitoring and characterization systems. There are numerous measurements that, depending on operational needs, are important for either directly or indirectly assessing reservoir performance. Sensing systems deployed in the subsurface are subject to many of the same temperature limitations as other subsurface technologies; this is a critical issue for all downhole systems, including logging tools, monitoring sensors, power sources, and telemetry systems. Temperature limitations need to be addressed across the board. Of note, and because of the importance of microseismic monitoring, is the lack of accelerometers and geophones that will function long-term at temperatures in excess of 225°C. If such equipment is not developed by industry, GTO will need to support RD&D in that direction. Fiber-optic-based sensing systems for measuring a variety of properties (e.g., temperature, pressure, and strain) are expanding rapidly. These systems can produce enormous amounts of data and methods to effectively handle those data need to be advanced; this includes the application of machine-learning algorithms to process and interpret data (see previous discussion and Section 2.6.2.1). Opportunities to advance the integration of monitoring systems with completion technologies should also be investigated (e.g., instrumented casing). Advanced tracers and associated diagnostics to inform fluid-flow paths and contact time are candidates for additional development. In addition, surface, airborne, and space-based technologies for reservoir monitoring should be assessed and integrated into characterization and monitoring systems.

2.4 Resource Maximization

2.4.1 Introduction

Geothermal resources are playing an increasingly multi-faceted role by contributing to U.S. grid reliability, resilience, and security; supporting development of a robust domestic clean energy manufacturing supply chain; and providing effective alternatives to grid-dependent heating and cooling as well as energy storage solutions for the built environment. Geothermal's breadth of applications—as a source for both critical materials and thermal energy storage—is critical to tackling the climate crisis.

GTO has a strong history supporting RD&D across the geothermal application space, and the value of continuing to do so is clear. Focused RD&D increases the ability to accurately capture geothermal energy resource value across all types and application spaces to maximize the use of such resources, in turn helping geothermal applications meet the *GeoVision* analysis goals and benefit a rapidly decarbonizing U.S. grid and economy.

Most recently, GTO has supported RD&D to maximize geothermal resource value through technology development (i.e., physical coupling as well as modeling and strategic analyses). Since 2014, GTO has funded two competitively awarded RD&D solicitations focusing on strategic mineral recovery from geothermal brines through novel sorbent and substrate technologies, as well as better resource characterization for critical materials and rare earth elements in U.S. geothermal and oil and gas resources (Stringfellow and Dobson 2020). However, while these novel approaches show promise, these technologies as well as the broader industry's demonstration of mineral recovery from geothermal brines remain pre-commercial. Recently, the DOE Advanced Manufacturing Office and the California Energy Commission have separately made awards to commercial geothermal operators in the Salton Sea region of California to demonstrate pre-commercial capabilities for direct lithium extraction from geothermal brines.[5, 6] More broadly, despite providing initial promising indications, understanding the value of bringing such resources to market has yet to be fully considered. Through collaboration across EERE, GTO undertakes techno-economic assessments of geothermal brine extraction technologies to better understand this value proposition.

There is ubiquitous thermal energy storage available in the Earth to deploy for a variety of direct-use and grid applications that can enable new, more resilient energy services that provide an effective alternative to grid-dependent heating and cooling and add climate resilience to the broader energy system. GTO supports this potential in partnership with the DOE Energy Storage Grand Challenge and through standalone funding opportunities for large-scale resource assessment and feasibility research across public and private institutions pursuing campus-wide geothermal system installation. Through advanced resource characterization and optimized system designs that incorporate site supply and demand profiles and align with increasing calls for installing climate-resilient infrastructure, GTO seeks to unlock the vast potential for moving geothermal beyond the western United States to a true national energy solution.

These efforts have also resulted in a variety of analytical tools to estimate geothermal project costs and performance, model future grid-capacity expansion and dispatch of generation resources in collaboration with multiple EERE offices, visualize potential geothermal deployment forecasts for the United States, and empower state and local energy planners to choose effective mixes of clean energy resources. These tools benefit the ability to accurately capture the value of geothermal energy resources but are informed by and complement work in other activity areas such as DMA (Section 2.5).

Technical Objective

Accurately capture the value of geothermal energy resources

Challenges and Barriers

- **Incomplete electricity market valuation:** unclear picture of geothermal energy's potential role in grid reliability and resilience
- **Inadequate representation in grid models:** data uncertainties that result in an overall inability to model technology advancements
- **Lack of cost-effective recovery and hybrid technologies from geothermal brines:** difficulty translating well-known potential into commercial deployment
- **Lack of design, installation, commissioning, and inspection standards for geothermal heating and cooling applications:** hindered valuation and market-expansion potential
- **Need to expand education and outreach:** limited opportunities to convey the role geothermal can have for achieving an energy-diverse, low-carbon U.S. future

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[5] https://www.energy.gov/eere/amo/advanced-manufacturing-office-fy20-critical-materials-foa-selections-table

[6] https://www.energy.ca.gov/news/2020-05/geothermal-lithium-recovery-projects-get-boost-california-energy-commission

Table 2.7 highlights GTO subprogram contributions in Resource Maximization RD&D toward meeting overall GTO program goals. The majority of the RD&D that will be conducted on grid valuation, thermal storage and utilization, and capturing additional geothermal value streams will be through the Low-Temperature and Coproduced Resources and DMA subprograms where there will be a primary and direct impact on achieving all three Strategic Goals.

Table 2.7. GTO Subprogram Contributions in Resource Maximization RD&D for Meeting GTO Strategic Goals

Resource Maximization	Enhanced Geothermal Systems	Hydrothermal Resources	Low-Temperature and Coproduced Resources	Data, Modeling, and Analysis
Goal 1: Drive toward a clean, carbon-free electricity grid 60 GW of EGS and hydrothermal resource deployment by 2050				Validate grid value of geothermal power generation, hybridized systems, and geothermal heating and cooling
Goal 2: Decarbonize building heating and cooling loads by capturing the economic potential for 17,500 GDH installations and by installing GHPs in 28 million households nationwide by 2050			Validate grid value of geothermal power generation, hybridized systems, and geothermal heating and cooling	
Goal 3: Deliver economic, environmental, and social justice advancements through increased geothermal technology deployment	Demonstrate through grid-scale and demand-side modeling, demonstration projects, and data collection and analysis the critical role geothermal energy will have in driving down economy-wide carbon emissions while delivering economic and environmental justice in a deeply decarbonized future			

Green: GTO subprograms with primary Research Area contributions toward GTO Strategic Goals

Gray: GTO subprograms with secondary Research Area contributions toward GTO Strategic Goals

No fill: GTO subprograms with tertiary Research Area contributions toward GTO Strategic Goals

2.4.2 Highlighted Performance Goals

Table 2.8 outlines GTO milestones and performance goals through FY 2026 for increasing the ability to accurately capture geothermal resource value and maximize value across all applications.

Table 2.8. Resource Maximization Highlighted Performance Goals

Activity/Objective	Mechanism	Target FY to Achieve	Baseline (current status)
Increase geographic resolution of grid capacity, production cost, and other geothermal deployment analysis tools	Implementing ReEDS improvement packages (e.g., flexible scaling of temporal and spatial resolution) in collaboration with EERE offices. Continued support through interagency agreements with USGS for improved geothermal resource assessments.	FY 2022	Current models are limited to U.S. balancing authority areas and above.
Couple physics and cost-analysis capabilities to better represent geothermal development costs	Integrating standalone cost modeling tools like GETEM to EERE-developed platforms like System Advisor Model and adding coupled modeling capabilities.	FY 2023	Existing DOE geothermal cost models are limited to deterministic outputs and rely on underlying datasets that are not structured to allow for dynamic input or stochastic outputs.
Increase portfolio of critical material extraction technologies beyond Technology Readiness Level 7 capabilities	American-Made Geothermal Lithium Extraction Prize aims to find solutions that de-risk and increase market viability for direct lithium extraction from geothermal brines.	FY 2025	Recent strategic material research portfolios resulted in advancements primarily limited to Technology Readiness Level 5 and below. Broader industry capabilities remain pre-commercial.
Expand strategic partnerships with federal and non-federal partners to increase geothermal system application use nationwide	Collaborate with DOE's Federal Energy Management Program to conduct site characterization and development activities for demonstration and deployment of on-site geothermal projects at federal installations.	FY 2026	Current U.S. geothermal systems are limited to a few commercial hybrid plants, 23 district-heating systems, and GHP installations equaling 2% of the U.S. heating, ventilation, and air conditioning market.

2.4.3 Research and Development Pathways

2.4.3.1 Grid Valuation

Geothermal energy is a renewable and diverse domestic resource capable of providing reliable and flexible electricity generation. However, while there is a long recognition of geothermal's traditional role as an "always-on," baseload resource, the value of that primary service as well as broader recognition of geothermal's ability to support numerous additional grid services has yet to be fully realized. While this challenge is likely the result of a combination between technology and market considerations, it is exacerbated by a lack of available, updated, and robust datasets on geothermal technology performance and cost. Additionally, there is a need to improve the representation of geothermal technologies within grid projection and energy planning models in a way that would allow geothermal's present and future value to the U.S. grid to be evident to stakeholders. Some of these data limitations are the result of the subsurface nature of the resource. Advancements in exploration, characterization, and development technologies and methodologies discussed in Sections 2.2–2.4 can help mitigate uncertainties with understanding resource potential that in turn can inform cost models.

Developing analysis and modeling capabilities that maintain, update, and create new approaches for accurately representing the current and potential value and benefits of geothermal energy to the U.S. grid can help better represent geothermal on the grid, particularly when incorporating results from technical innovations. Greater representation of geothermal also enables a more secure path toward deploying the 60 GW_e by 2050 identified in the *GeoVision* analysis Technology Improvement scenario. To achieve this goal, it will be essential to understand the projected value of geothermal energy to the future U.S. grid. This can be achieved through a comprehensive effort that develops and implements new and improved modeling approaches and capabilities that accurately represent geothermal technology performance and costs.

Collaborating with DOE and external stakeholders is an overarching goal for all GTO Research Areas, but building close partnerships is particularly important for research in this section given the inherent interconnectedness of grid research; the importance in improving linkages between grid modeling communities, GTO, and the geothermal industry; and the need to ensure such efforts are complementary to broader DOE initiatives. Organizations and initiatives involved in these efforts could include but are not limited to EERE's Renewable Power offices and its Strategic Analysis Office as well as DOE's Energy Information Administration, national laboratories, Grid Modernization Initiative, and Energy Storage Grand Challenge.

The subsequent technical areas are of notable research interest through FY 2026 for grid valuation.

Enhance geothermal representation in grid and cost models. Geothermal resources are unique in the renewable power world, with inherent uncertainties that require a range of technologies for successful exploration, development, and operations. Representing and minimizing these resource uncertainties are key motivations across all technology focus areas highlighted in this document, including grid and geothermal project cost models. Geothermal representation in existing models can lack geographic or temporal resolution and contain largely deterministic input datasets that limit project representation abilities or are burdened by significant project cost uncertainties. Additionally, inputs can translate poorly between grid projection models. Given the vast number of public and private stakeholders that rely on these types of models, it is imperative to enhance geothermal representation to accurately capture its potential grid value. To do so will require exploring approaches that:

- Introduce higher-resolution geographic modeling capabilities to improve relevant representation in system-wide grid models, particularly at the sub-balancing authority area (sub-BAA) level
- Capture improved data fidelity on geothermal resource development costs by pursuing new data-collection efforts while also ensuring DOE-funded project data for initiatives such as FORGE are comprehensively captured
- Explore approaches to introduce physics-based and stochastic modeling capabilities into geothermal cost models
- Improve data-sharing ability between geothermal cost models and capacity-expansion models.

Validate models and characterize uncertainty. Accurately capturing geothermal values in grid and cost models is not accomplished solely through enhanced data collection or data-sharing capabilities; the means of applying these data for a given model must also minimize output uncertainties. For example, the Geothermal Energy Technology Economic Model (GETEM), a GTO-developed geothermal project cost model, is a robust tool for providing a variety of estimations for project costs associated with geothermal development. However, GETEM is deterministic in its calculation for a given project. While there are a variety of available inputs to describe geothermal project costs, the model lacks the flexibility to easily incorporate new datasets that can provide greater certainty in modeled cost outputs. Furthermore, GETEM is not rigorously tied to the physics or thermodynamics of the physical system, where cost-based parameters are highly interrelated and dynamically coupled. For example, stimulation costs are represented through a simplified set of inputs that do not incorporate the full spectrum of variables to consider during an operation (e.g., number of stimulation stages). Introducing physics-based capabilities can enhance model sophistication and minimize uncertainties from incorporated datasets, enhancing the ability of models such as GETEM to incorporate and expand available inputs. When accomplished in coordination with GTO initiatives such as FORGE, technical achievements can be better represented in GTO-funded models that more accurately reflect how such advancements lower geothermal levelized cost of electricity.

Improve capacity expansion and production cost modeling. Enhanced collaboration with internal and external stakeholders can move development of capacity-expansion models beyond current capabilities. Existing DOE-developed capacity-expansion models are restricted to average system behavior incorporated over a BAA, with no ability to model at a sub-BAA scale. This limits the ability of models to examine important regional- and market-based constraints and impacts on geothermal deployment, e.g., in important active development regions such as California and Nevada. Additionally, learning-by-doing improvements are represented as an assumed fixed rate or other type of manual input and are not calculated by the models. To improve the ability to accurately capture geothermal's value to the U.S. grid, research can focus on a few different options that integrate grid services pricing into the National Renewable Energy Laboratory's (NREL) Regional Energy Deployment System, or ReEDS. This will allow for better projections of service demand with increasing variable generation resources, as well as improve and create entirely new linkages between existing models for the spectrum of geothermal technologies that can benefit the U.S. grid.

Develop and demonstrate geothermal grid service technologies. Enhancing the value geothermal provides for the U.S. grid will require analysis to accurately capture geothermal value as well as research and demonstration of plant or facility infrastructure and operation designs to fit any number of grid services. Important analysis considerations to further define potential technology research focuses include understanding the techno-economics from integrating generation resources virtually or via on-site generation, understanding the extent for how geothermal operators participate in ancillary service markets, developing analytical capabilities that can determine optimized economic value and operational efficiencies for a range of geothermal grid services, and market and regulatory analysis.

Such analysis can inform GTO research and demonstration for understanding market participation options that maximize geothermal energy storage deployment and developing a range of potential geothermal technologies for the benefit of providing grid services, such as geothermal abilities to meet a range of ramping rates required to provide frequency regulation. Demonstrating these capabilities is closely linked with geothermal's as-yet-untapped potential as a significant thermal energy storage option (see Section 2.5.3.2 for thermal storage and utilization technology development needs).

2.4.3.2 Thermal Storage and Utilization

In addition to the significant standalone electricity-generation potential from U.S. geothermal resources, these resources also hold significant potential to bolster climate resilience and provide numerous energy services—including energy storage as well as heating and cooling applications for the built environment. However, full demonstration of the breadth of these technology applications has yet to be realized. An established GHP industry exists across the United States supporting currently installed capacity of 20.2 GW_{th} (Lund et al. 2020). However, the DOE's *GeoVision* analysis demonstrates the potential for this installed capacity to reach as much as 151 GW_{th} (*GeoVision* Breakthrough Scenario) with improved technologies. Additionally, despite geothermal direct-use economic resource potential in excess of 320 GW_{th}, only about 100 MW_{th} of geothermal direct-use resources have been deployed for district heating in 21 installations across the country (Snyder et al. 2017).

GTO is focused on enhancing understanding of how such systems can operate both efficiently and cost-effectively to meet evolving grid and heating/cooling needs, as well as better managing resource productivity. Such approaches will be necessary in helping to chart a path to develop geothermal as a true "anywhere" technology solution and capture the 320 GW_{th} in economically viable district-heating resource potential outlined in the *GeoVision* analysis. An overarching goal for all research activities discussed in this section is increased collaboration with federal partners to identify opportunities for deploying on-site geothermal systems that satisfy federal energy and fuel security demands while demonstrating how geothermal can significantly contribute toward advancing a low-carbon energy future, noting the significant impact potential and unique levers the federal government has in cultivating new energy technologies.

For purposes of the MYPP, hybrid technologies are defined to combine two or more energy types and/or produce two or more products to overcome limitations inherent in the respective stand-alone systems. Integrating multiple technologies can enhance performance capabilities, resource values, and/or cost savings compared to standalone geothermal power plants or conventional heating and cooling options for the built environment. These applications can contribute to the two focus areas in this section. Additionally, while district-heating systems and GHPs operate for the benefit of similar thermal storage and utilization goals, they have yet to be fully integrated for single-site installations. Given increased sophistication in building technologies, software, and geothermal resource management, an overarching goal will be examining the potential to research system designs that can incorporate both technology spaces.

The subsequent technical areas are of particular research interest through FY 2026 for thermal storage and utilization.

Identify additional roles for and increase the use of geothermal heat pumps in storage. GHPs harness the principles of constant near-surface temperatures to discharge and extract heat at advantageous times of the year, facilitating thermal storage on scales ranging from single family homes to facility-wide installations. While aspects of the U.S. GHP industry are established, continued research is needed to further understand the application's potentially significant role in reducing campus-scale building energy use while also satisfying heating and cooling needs. Harnessing computational modeling approaches that can improve system configurations by incorporating parameters such as weather forecasting, spot electricity pricing, and occupant learning behavior can optimize system design and performance. The ability to standardize and lower the cost of system design and installation will benefit from research into novel installation geometries and improved automation.

Equally important with advancing technologies will be improving overall public awareness and increasing consumer acceptance of geothermal heating and cooling systems. These systems are existent, low-carbon energy solution that can offer additional roles, such as improved energy storage. Developing research strategies that emphasize this value with the broader public can have measurable impact in sparking vast near-term geothermal resource use potential. Increasing public awareness can reduce risk, in turn allowing for procurement options either currently available to or underutilized by the GHP industry. Analysis can help confirm where innovative approaches (e.g., vertically integrated installation companies) or third-party equipment ownership might better support full GHP market uptake.

Increase the use of geothermal district heating and cooling systems. While district-heating systems leverage the same thermal properties found in the subsurface, their use cases expand to a variety of beneficial applications, such as better meeting end-use demand profiles and providing flexible energy-storage options. Other applications in this focus area include bi-directional energy storage, direct use, deep direct use, reservoir thermal energy storage, aquifer thermal energy storage, borehole thermal energy storage, and advanced energy storage.

Delineating the effectiveness between optimal and suboptimal district heating and cooling systems will require modeling capabilities that account for reservoir and thermal saturation response for different phase fluids and use cases. This will require consideration of parameters such as expected storage time durations, energy intensity loads, and thermal recovery efficiencies to better delineate effective geothermal storage and utilization applications. Linking such modeling capabilities to surface infrastructure (e.g., commercial buildings or campuses) can incorporate the advancements of novel building energy management technologies with a geothermal district heating and cooling system to optimize a system's demand profile response. Additionally, system designs at all subsurface depths (i.e., meters to hundreds of meters) can leverage the drilling, wellbore materials and construction, and resource development research advancements discussed in Sections 2.3 and 2.4 to improve project economics.

As discussed in the *GeoVision* roadmap, understanding the market potential of district heating and cooling systems will require a robust analysis of market adoption rates. The information available for conducting market potential-based assessments of heating and cooling applications has historically been restricted to general behavior of individual consumers, e.g., those who might install rooftop solar. However, district heating and cooling technologies tend to be deployed at the community level. The adoption behaviors of district versus individual groups differ, and community decision-making behavior related to heating and cooling technology adoption is not well understood. District heating and cooling systems are more widely adopted in Europe, where associated consumer behaviors have been studied and may serve as a general guide for understanding the potential for such systems in the U.S. Quantifying the market potential and possible roles of geothermal direct-use applications can raise awareness of the technology and encourage use of renewable, geothermal direct-use heating and cooling solutions in U.S. communities.

2.4.3.3 Value Streams

Developing new geothermal value streams can bolster the economic competitiveness of geothermal resources while also aiding U.S. clean energy manufacturing supply chains and water supplies. Value-stream areas of interest such as critical and strategic minerals extraction have historical roots that stretch even before development of the first U.S. geothermal resources. Other value streams, such as the opportunity to integrate with clean fuel manufacturing or commercial-scale desalination technology and operations are newer in their overall development. Regardless, none of these value streams have yet to be fully explored and realized. Pursuing research described in this section will require exploring both technology and analysis approaches to identify cost-effective pathways for advancing promising geothermal added-value streams and to diversify geothermal development options.

Investigate opportunities for critical materials recovery. Significant increases in market demand for critical materials such as lithium, combined with the low number of U.S. resources currently available for sourcing these materials, underscores the strategic importance for the United States to identify new upstream critical materials resources and to advance economically competitive critical and strategic material extraction from resources such as geothermal brines. Previous research has shown that critical and strategic materials exist in economic and sub-economic quantities across the western United States (Simmons et al. 2018). Within this region, California's Salton Sea represents an outsized opportunity to diversify the domestic supply chain of minerals, particularly lithium, with an estimated 170,000 metric tons of lithium-carbonate annual production potential valued at $2.3 billion (Wendt et al. 2018). However, ongoing challenges exist in accurately characterizing brine resource constituents and production sustainability, representing brine complexities necessary for bench-scale experiments and process engineering that pretreats geothermal brine effectively. To better address these challenges and unlock materials resource potential, research efforts through FY 2026 can build on prior GTO work in resource characterization and development of technologies that selectively remove critical materials from brines. These RD&D focuses can help enhance data collection that leads to improved understanding of the co-location of lithium and other critical materials and hidden geothermal resources, while advancing extraction technology systems that integrate with geothermal power-plant configurations and operations. Additionally, underpinning analysis should continue to develop understanding of the impact potential that cultivating such technology can have on building out a robust U.S. clean energy manufacturing supply chain.

Assess the potential for geothermal desalination. Using geothermal energy to drive desalination operations can increase operational efficiencies in providing potable water for industrial or municipal purposes. This can be especially true for geothermal resources in regions of the United States that are experiencing increasing aridity and may provide growing opportunities as markets and policy shifts occur. The intersection opportunity of desalination and geothermal, however, remains application and location dependent. While initial analyses suggest competitiveness with alternative water-disposal methods, further analyses should build on these results to better understand market values and constrain project costs. Such project cost information is beneficial to include as input into DOE-supported geothermal project cost models such as GETEM. Additional refinement of existing thermal desalination technology—as well as development of new technology—can be explored in conjunction with DOE initiatives such as the Advanced Manufacturing Office-led National Alliance for Water Innovation.

Evaluate the value of hydrogen production from geothermal. Geothermal energy, in tandem with other energy resources, can produce hydrogen (H_2) fuels as a demand-response grid activity, in turn, diversifying the H_2 fuel-supply chain. The temperatures required for hydrolysis processes fall within the operational conditions of many high-temperature geothermal resources—particularly for states such as California, where the largest U.S. H_2 market currently exists. A recent resource assessment for H_2 production potential indicated 483.8 MMT per year of H_2 production potential from geothermal resources (Connelly et al. 2020). Expanding H_2 applications will require close alignment and coordination with broader DOE efforts led by the Hydrogen and Fuel Cells Program. This includes ongoing work with H_2 market economy maturation to further commercial deployment of H_2 production sites using geothermal energy.

Research priorities in the H_2 space are similar to analyses outlined for other value streams discussed in this section; that is, process engineering to ensure that these additions enhance the value of the overall operations. Additional analysis for hybridizing geothermal with complementary energy resources such as solar could be an important potential use case for H_2 production given the confluence of existing markets for geothermal and solar, abundant additional resource potential, and leading-edge domestic commercial markets in the western United States.

2.5 Data, Modeling, and Analysis

2.5.1 Introduction

Data collection and analyses are at the core of GTO's RD&D activities. Data assessment supports decision making, demonstrates progress toward goals, helps identify and characterize challenges, and directs research activities. Robust, well-organized, and accessible data are crucial to geothermal research and deployment. For instance, publicly available datasets related to risks, procurement costs, and other nontechnical barriers empower stakeholders and decision makers with the information required for making decisions about geothermal projects. Other data essential to geothermal research include resource and infrastructure analysis, technical and economic feasibility, risk assessment, and benefits analysis.

GTO's DMA subprogram provides a critical supporting and enabling function toward advancing the entire GTO research portfolio. Data are important to support current GTO activities and help plan for future activities; therefore, many DMA objectives and activities align with or even overlap those in other GTO Research Areas. For instance, DMA insights on added value streams for geothermal links directly to building out demonstration work in Resource Maximization.

The DMA Research Area focuses on increasing both the quantity and quality of data underlying GTO's portfolio, as well as improving the architecture and infrastructure through which geothermal-related data are used, communicated, and fed to other DOE-developed models (e.g., GETEM, ReEDS). DMA activities can also help GTO track progress against metrics and goals.

Led by the DMA team, the *GeoVision* analysis was a key milestone for GTO, assessing the potential future of domestic geothermal energy and identifying pathways to reach that future. Some other key activities being led or planned by DMA to support GTO objectives include:

- Overseeing the Geothermal Design Challenge, in which students from high schools, universities, and colleges across the United States analyze data from the Geothermal Data Repository and use GIS to design maps highlighting the untapped potential of geothermal energy
- Developing and supporting economic impact and modeling tools for cost and performance as well as models that identify and simulate the potential for use of geothermal energy resources
- Examining historical trends of power purchase agreements (PPAs) for acquisition of geothermal energy and innovative procurement structures for geothermal projects within shifting domestic PPA landscapes

Technical Objective

Expand capabilities of using data to identify and address barriers to geothermal deployment

Challenges and Barriers

- **Insufficient geothermal project and cost data:** challenges managing risk due to a lack of performance and cost data
- **Lack of representation in modeling tools:** inaccurate technology cost representation that limits the competitiveness of geothermal energy
- **Insufficient economic analysis of geothermal value streams:** higher financing costs due to inadequate understanding of revenue streams for geothermal
- **Incomplete data and collaboration regarding permitting or other regulations related to geothermal:** barriers to geothermal development resulting from a lack of clarity in how permitting requirements, building codes, and other systems affect geothermal projects
- **Lack of geothermal awareness**: low visibility and limited use due to a lack of clear and digestible information about geothermal and its value to the nation

- Assessing how geothermal project development aligns with responsible environmental management and stewardship and can contribute to a low-carbon energy future
- Collaborating with DOE's Weatherization and Intergovernmental Programs to incorporate geothermal resource assessment capabilities into community energy planning tools such as the State and Local Planning for Energy (SLOPE) platform.

Work in GTO's DMA portfolio is often conducted in collaboration with other EERE offices and initiatives such as the EERE Strategic Analysis Office and the Energy Storage Grand Challenge to help meet GTO objectives and support alignment with broader EERE priorities.

Table 2.9 highlights GTO subprogram contributions in DMA RD&D toward meeting overall GTO program goals. Most of the planned RD&D on geothermal data curation and dissemination as well as technology, market, and policy RD&D will be through the DMA subprogram where there will be a primary, direct impact on achieving all Strategic Goals. All other subprograms contribute to achieving the Strategic Goals at a secondary level through critical data creation, coordination, and collaboration with the DMA subprogram.

Table 2.9. GTO Subprogram Contributions in Data, Modeling, and Analysis RD&D for Meeting GTO Strategic Goals

Data, Modeling, And Analysis	**Enhanced Geothermal Systems**	**Hydrothermal Resources**	**Low-Temperature and Coproduced Resources**	**Data, Modeling, and Analysis**
Goal 1: Drive toward a clean, carbon-free electricity grid 60 GW of EGS and hydrothermal resource deployment by 2050	▨	▨	▨	Collect, model, and analyze data that validates grid and additive value of geothermal power generation, hybridized systems, and geothermal heating and cooling
Goal 2: Decarbonize building heating and cooling loads by capturing the economic potential for 17,500 GDH installations and by installing GHPs in 28 million households nationwide by 2050	▨	▨	▨	
Goal 3: Deliver economic, environmental, and social justice advancements through increased geothermal technology deployment	Perform enabling data collection, modeling, and analysis that documents the critical role geothermal energy will have in driving down economy-wide carbon emissions while delivering economic and environmental justice in a deeply decarbonized future			

Green: GTO subprograms with primary Research Area contributions toward GTO Strategic Goals

Gray: GTO subprograms with secondary Research Area contributions toward GTO Strategic Goals

No fill: GTO subprograms with tertiary Research Area contributions toward GTO Strategic Goals

2.5.2 Highlighted Performance Goals

Table 2.10 outlines key GTO performance goals through FY 2026 to support effective execution of DMA's activities.

Table 2.10. Data, Modeling, and Analysis Highlighted Performance Goals

Activity/Objective	Mechanism	Target FY to Achieve	Baseline (current status)
Complete a full assessment of the value of geothermal electricity generation to the grid, including ancillary services	Leverage findings of FY 2021–FY 2022 nontechnical barriers work to design analysis and modeling program to capture the full value of geothermal energy to the grid	FY 2023	Current valuation models and purchasing vehicles do not fully account for the price-value gap of geothermal electricity generation.
Implement real-time interface capabilities among GTO analytical tools and the Geothermal Data Repository	Leverage ongoing high-value geothermal data integration into the Geothermal Data Repository and directly connect with geothermal analysis tools such as GETEM	FY 2023	Geothermal Data Repository data are available for use in DOE-developed analytical tools but must be input manually.
Significantly improve geothermal permitting timelines	Develop interagency collaboration task force, instantiate regional permitting working group, and conduct analysis for geothermal deployment on federal lands	FY 2025	Permitting timelines are a significant barrier to geothermal development and can force projects into National Environmental Policy Act review as many as six times.
Support new high-resolution resource assessments across the geothermal spectrum	Coordinate with USGS and other research partners to prioritize resource assessment update needs	FY 2026	Existing geothermal resource assessments are outdated and/or do not fully address the geothermal resource spectrum.

2.5.3 Research and Development Pathways

2.5.3.1 Economic Analysis and Validation

Economic analysis is essential to advancing geothermal deployment. Geothermal energy projects are often at a disadvantage because their costs are compared to other generation technologies using metrics such as levelized cost of electricity or capital expenditures, neither of which accounts for the value of firm, renewable generation resources in an increasingly decarbonized grid. Nor do these metrics appropriately value geothermal energy's attributes as a flexible resource or its ability to provide ancillary services. Understanding the true costs of and potential value and revenue streams for geothermal energy helps identify viable opportunities for the technology and allows developers to make decisions about which geothermal projects have the highest potential for near- and long-term economic success. In addition, a better understanding of the economics of geothermal energy can assist in overcoming market barriers—a significant nontechnical concern for geothermal deployment. Providing comprehensive, credible ways to measure the market value and contributions of geothermal energy is an essential role for GTO's DMA subprogram.

The market competitiveness of an energy technology is assessed by evaluating its implementation and capital costs and its expected revenue streams against the costs of other energy technologies. As noted, geothermal energy projects are often at a disadvantage because their full economic value is not well understood. Potential revenue streams for geothermal do not always balance upfront capital costs sufficiently, and geothermal projects are often subject to expensive financing terms (or a lack of financing altogether). Analyses that are informed by technology advancements and provide a more consistent and comprehensive assessment for geothermal energy can offer more certainty, in turn helping developers secure more attractive financing. In addition, ongoing market analyses and trend reports can help GTO understand areas for future geothermal research, potential applications, and market opportunities.

The following paragraphs describe areas of research interest through FY 2026 for economic analysis and validation.

Assess opportunities for innovative financing. Accessing capital and acquiring PPAs is the greatest nontechnical barrier to geothermal projects being developed in the United States (Wall and Young 2016). Established utility procurement practices, including those for PPAs, have not historically reflected some attributes and services offered by geothermal power, such as dispatchability. Existing renewable energy financing processes and related supporting studies and findings often compare generation technologies on a cost-per-kilowatt-hour or capacity basis—for example, using levelized cost of electricity. As generally applied, levelized cost of electricity does not reflect the specific grid attributes of some technologies and is therefore difficult to compare across all technologies (Linvill et al. 2013, Energy Information Administration 2015). For instance, while it is physically possible for geothermal power plants to operate flexibly, traditional PPA terms do not make it cost effective to do so. The inability to fully calculate the value of geothermal energy can reduce its procurement options and artificially suppress the value a geothermal power plant can bring to the electricity grid.

Analysis under the DMA subprogram can help GTO and its stakeholders gather data to inform financing and market pricing mechanisms that better account for the full value of geothermal to the grid and consumers. These assessments are essential across the geothermal resource spectrum. Having GTO produce those analyses can help ensure objectivity and public availability of data that is otherwise often privately held. Doing so can increase access to data and ultimately lead to better market acceptance.

Analyze revenue opportunities for added value streams. As noted in Section 2.4.3.3, developing additional value streams for geothermal energy can bolster the technology's economic competitiveness while providing other benefits, including aiding U.S. clean energy manufacturing supply chains and water resource supplies. Comprehensive analyses of these potential value streams will provide objective and concise detail for developers, energy planners, utilities, and other stakeholders—in turn helping to encourage geothermal development and improve geothermal project economics for both the electric and nonelectric sectors. Continuing DMA research in this area will provide analytical support to the activities and potential value stream areas discussed in Resource Maximization (Section 2.4), including critical materials recovery, water desalination, and H_2 production. DMA analyses may also contribute to models that assess geothermal-hybrid systems.

Prepare market report and trend analyses. Additional project analysis work is necessary to baseline, document, and report on electric and non-electric market sector trends. Such trends include assessing market size, industry developments, future market projections, inventories and operational characteristics of current and potential suppliers and other market participants; evaluating impacts of policy and incentives; and identifying pathways to increased collaboration with other energy or natural-resource industries (e.g., mining, oil, and gas).

2.5.3.2 Data Collection, Access, and Analysis Tools

As noted, analyses to support geothermal deployment are crucial, and executing solid analyses requires reliable, comprehensive tools. There are numerous tools available for energy analysis and planning, but not all tools include or properly account for geothermal energy. For instance, energy performance and cost models have not historically included geothermal, and, when they have, geothermal is not always accurately represented due to a lack of sufficient high-quality data. The DMA subprogram will continue to build and contribute to data analysis tools that increasingly include and better represent geothermal energy. This work will comprise capacity-expansion modeling tools for electricity generation, such ReEDS, as well as models that facilitate better understanding of the economic conditions for and value of nonelectric sector technologies (GHPs and direct-use systems).

Activities of focus through FY 2026 for data collection, access, and analysis are described in the following sections.

Improve geothermal project cost and performance data. There is a need to consistently improve upon data and seek new, diverse sources to ensure higher fidelity data related to cost and performance across the geothermal resource spectrum. Data can be used to make better decisions for operations and maintenance of existing geothermal facilities, support improved resource planning activities that capture accurate geothermal performance data such as capacity factors, point to opportunities for more detailed RD&D, and provide information and understanding for consumers.

Future studies can focus on gathering field performance data from projects across the geothermal use spectrum, which is important to reduce risk—in turn enabling third-party financing and other policies related to financial incentives. Such performance data can provide valuable insights to assess the impact of state policies on geothermal deployment and can help identify new technology development pathways for improving system cost and performance.

Key underpinning datasets collected through this activity will support model fidelity, an important facet of performance cost modeling as discussed in the following activity.

Advance performance cost modeling capabilities. In addition to ensuring access to and collection of improved data, DMA research will support improving the tools by which such data are modeled and analyzed to calculate performance cost. DMA has and will continue to address gaps in performance cost modeling for geothermal, with focus on enhancing geothermal representation in such models. These improvements will enhance GTO's ability to ensure that RD&D investments are appropriately prioritized based on impact.

Tackling the cost-reduction impacts of technology improvements is fundamentally challenging for geothermal. Geothermal cost-model inputs are highly interrelated with one another and across multiple scales and phases of development. These inputs must also be tied rigorously to the subsurface physics of the system and provide some level of statistical analysis capabilities, which is presently lacking in available deterministic tools (e.g., GETEM). As an example, project drilling costs can be decreased by technology improvements that directly lower the per-well drilling costs or through improvements in reservoir creation that increase well productivity and decrease the number of wells required for the projects (DOE 2019). As such, improvements to performance cost modeling are important for advising RD&D investment decisions in the Exploration and Characterization Research Area. As noted in Section 2.1, additional cost- and performance-based modeling analysis could help drive understanding with respect to which specific combinations of geophysical, geological, or geochemical technology improvements can yield the most impactful cost reductions.

Another example of investments in techno-economic analysis capabilities is GTO's support to create the Distributed Geothermal Market Demand model (dGEO). dGEO is a long-term scenario-modeling tool that can simulate the technical, economic, and market potential and the technology deployment of GHP and GDH applications. The model uses input scenarios that consider changes in costs, performance, and financing; costs of heating and cooling alternatives; and heating and cooling energy demand and the potential of geothermal resources to meet that demand. Continuing to assess the need for and creating models such as dGEO is an important role for the DMA subprogram.

Assess cybersecurity and vulnerability. The mission of DOE's cybersecurity activities includes ensuring a secure and reliable critical energy infrastructure. As needed, GTO's DMA subprogram will assess topic areas where geothermal energy can help strengthen the electricity grid and will identify, analyze, and mitigate cyber-related vulnerabilities in geothermal energy systems.

2.5.3.3 Policy and Regulatory Analysis

Geothermal energy is strongly impacted by nontechnical barriers. In the electric sector, geothermal energy is impacted most notably by barriers such as market conditions (e.g., PPA acquisition), land access and permitting, lack of access to transmission infrastructure, and delays in obtaining project financing (Wall and Young 2016). Data are crucial to expanding understanding of these barriers and their impact on geothermal development. In the nonelectric sector, geothermal is impacted by barriers such as competition from alternative heating sources, high initial upfront costs, and poor public awareness. The DMA subprogram cannot write or suggest policy but can provide detailed analyses on nontechnical barriers that will give stakeholders the necessary insights to make informed decisions.

DMA portfolio will build on existing analyses and expand collaboration with relevant stakeholders to examine ways to overcome geothermal barriers.

Reduce development timelines through analysis and interagency collaboration. The lengthy timelines associated with permitting geothermal projects are a significant barrier to the technology's electric-sector development (Young et al. 2019). Long permitting timelines and multiple environmental reviews increase risk and cost for developers and discourage financiers seeking low-risk, near-term-return investments that can stifle overall geothermal development potential. DMA will prioritize focused activities that support coordination between GTO and relevant federal and state agencies to analyze opportunities for solutions that can help advance geothermal while adhering to environmental guidance and other stakeholder needs. DMA activities in assessing geothermal permitting will rely on collaborative processes, thorough and objective analysis, and consideration for a range of stakeholder needs.

Reduce nontechnical barriers. As noted, geothermal energy development in both electric and nonelectric sectors is impacted by a range of nontechnical barriers. For example, geothermal energy is impacted across the resource spectrum by a lack of awareness and acceptance, particularly in comparison to other renewable technologies. Wind turbines and solar panels are familiar, often large structures that provide tangible evidence of the use of those natural resources for energy. In contrast, the public is generally unaware that geothermal resources exist and can be used for a wide array of energy applications. Both electric and GHPs installations are generally smaller than comparably sized renewable energy projects, while district heating and cooling systems may be more visible in terms of size, but often serve buildings from which the installations cannot be seen. In addition, geothermal systems tend to have higher upfront costs and generally cannot benefit from tax credits or other incentives.

DMA will continue to support high-fidelity data and detailed analyses. The resulting objective assessments can help geothermal stakeholders develop new programs or technologies to overcome nontechnical barriers. For example, analyses could be conducted to evaluate the long-term cost savings for using GHPs or geothermal electricity across numerous installations, providing a menu of options for deployment consideration by DOE and other geothermal stakeholders. Successful analyses in this activity can support other DMA work—for instance, by providing information on the best areas in which to offer technical assistance and/or energy planning (Section 2.5.3.4) or by linking to performance data (Section 2.5.3.2) for a better overall picture of the costs and value of geothermal energy.

2.5.3.4 Data and Analysis for Communication and Collaboration

Expanding the use of geothermal will require overcoming the lack of awareness noted in Sections 2.6.2.5 and 2.5.3.1. Effectively communicating to consumers, businesses, and investors about how the uses and benefits of geothermal energy will require stakeholder collaboration and enhanced outreach. DMA activities can support better communication and collaboration by assessing areas of need, providing objective inputs to address awareness and other barriers, and centralizing coordination across GTO and with other stakeholders.

The following paragraphs discuss activities of focus through FY 2026 for using data and analysis for communication and collaboration.

Develop technical assistance and training resources. Work under DMA will assess the need for and effort required to develop and/or support technical assistance programs for stakeholders interested in geothermal. Such stakeholders could include federal, state, and local government organizations; universities and other large-campus users considering district-heating systems; and new developers or other electricity stakeholders interested in geothermal power plants. Technical assistance efforts could include coordination across GTO's Research Areas, including sharing research outcomes that enhance understanding of geothermal uses and technologies, as well as collaborating with partners seeking to deploy a range of geothermal technologies. In addition, GTO may coordinate with other federal programs (e.g., ENERGY STAR®) to address technical knowledge that can help stakeholders better assess geothermal applications.

Geothermal is also impacted by a shortage of geothermal professionals, consultants, and businesses along with a general aging of the existing geothermal workforce. Anticipated growth in geothermal development resulting from the efforts of GTO and other stakeholders will drive demand for a skilled workforce across the resource spectrum—from drilling operators to GHP installers. The DMA subprogram can work to assess regional needs for training and develop/contribute to educational programs and workforce development. This effort might include coordinating with universities, trade schools, unions, or other organizations to identify specific needs and structure relevant hands-on learning and apprenticeship programs. Technical assistance efforts may also include educating end users on how to assess geothermal use cases, potential, and/or feasibility.

Contribute to and develop energy planning tools. As noted in Resource Maximization (Section 2.4), there is an ongoing need to develop, contribute to, and improve GTO-supported geothermal cost models (e.g., GETEM, Sandia National Laboratories' GT-MOD), as well as external models as needed. Work in the Resource Maximization and DMA Research Areas are complementary, with each being essential to improve geothermal presence in modeling tools. Resource Maximization activities will help provide the fundamental baseline and performance data necessary, while DMA activities will help analyze data, communicate results to required stakeholders, and identify areas for new or expanded research. Work to improve energy planning and deployment tools will require collaboration among GTO Research Areas as well as with other stakeholders, including DOE's national laboratories, other federal agencies, universities, and others.

DMA work will include collaboration to improve geothermal representation in modeling tools and analyses such as GETEM, NREL's Annual Technology Baseline and Standard Scenarios, and others. GTO is also supporting data collection for the SLOPE tool in coordination with the Office of Weatherization and Intergovernmental Programs. Expanding the amount of geothermal data included in SLOPE will provide better information to state and local decision makers.

DMA analyses can help GTO create internal-facing metrics by ensuring accurate representation for geothermal under GPRA. These metrics can point GTO toward future research opportunities by measuring progress and identifying gaps. In addition, a key goal of the DMA subprogram is to identify ways to improve GTO's data architecture through better project-data integration across the GTO portfolio.

Conduct resource assessments across the geothermal spectrum. The subsurface nature of geothermal inherently increases the risk and costs of exploration and development. Significant exploration and capital expenditures are necessary to locate, characterize, and prove a geothermal resource. Comprehensive, updated resource assessments provide multiple benefits for driving down development risks by increasing dataset fidelity critical to resource exploration activities while also reducing uncertainty in how geothermal resource capacity potential is calculated in capacity expansion models. DMA activities through FY 2026 will include contributing to and building on past assessments of geothermal electricity resource potential by state and federal agencies. DMA activities will also expand assessments to include lower-temperature geothermal resources suited to direct-use applications, as well as resources for GHP applications that can help identify system value and market opportunities. This work may include, for example, an effort to collect high-resolution data on key soil properties for sizing ground heat exchangers and evaluating GHP economics (thermal conductivity and heat capacity)—data that have not previously been compiled with sufficient resolution at a national scale.

2.6 Geothermal Integration and Awareness

Technical Objective

Expand stakeholder engagement to improve understanding of geothermal energy and advance geothermal technologies

Challenges and Barriers

- **Need for workforce training, cost reductions, and advanced manufacturing across geothermal resource types:** limited access to trained workers and nascent advanced manufacturing innovations and other tools that could reduce costs for all geothermal resource technologies
- **Limited public awareness and understanding of geothermal:** only assumptions as to cause; therefore, no airtight strategy for addressing this challenge

2.6.1 Introduction

As discussed in the introduction to Section 1, each of GTO's subprograms focuses on a distinct aspect of geothermal energy and addresses challenges unique to those aspects. Several additional GTO activities, however, cut across multiple subprograms. Many of GTO's cross-cutting[7] activities are discussed in this MYPP within the Research Area to which they apply—e.g., Section 2.3 covers all Subsurface Accessibility research, whether it applies to geothermal electricity or GHPs. By contrast, this section highlights technology-agnostic activities GTO is undertaking to research specific opportunities that impact all GTO Research Areas.

2.6.2 Cross-Cutting Activities

2.6.2.1 Machine Learning

Machine learning techniques offer substantial opportunities to advance technologies while also reducing costs across all geothermal resource types and operational lifecycle stages. GTO funds a portfolio of projects that is harnessing a range of supervised and unsupervised machine learning approaches to improve and optimize geothermal exploration, resource characterization, drilling target identification, drilling practices, induced seismicity risk reductions, and operational efficiency improvements of geothermal power plants and associated well fields.

The value that machine learning can provide is linked directly to the quality of datasets available for input and analysis. GTO's existing machine learning research portfolio leverages a unique opportunity through collaboration with domestic and international commercial geothermal operators who are providing commercial drilling and field development datasets for research. Another substantial opportunity exists over the next five years given the number of field-based initiatives that are ongoing or will be developed (e.g., FORGE, exploration of hidden systems in the Great Basin). This confluence of step-changes in data-processing sophistication along with direct access to DOE-funded field datasets across a range of geothermal resources underscores the unique opportunity to continue driving formerly empirical observations and correlations toward predictive reservoir characterization and behavior.

In addition to potentially supporting field-scale activities over the next five years, machine learning techniques may have possible benefits for optimizing design and operational efficiencies of low-temperature geothermal resources (e.g., predictive behavior adaptation by GHP systems). Machine learning may also contribute to other areas that are of strategic interest but suffer from data sparseness, e.g., geothermal resource assessments. GTO's machine learning activities include collaboration with relevant stakeholders, including federal partners. Using machine learning to characterize and correlate key geothermal resource parameters, e.g., temperature and ground thermal conductivity, can reduce geothermal resource uncertainty—and, in turn, lower exploration risks and improve resource identification.

2.6.2.2 Advanced Manufacturing

Geothermal environments can pose manufacturing challenges for creating tools and components because they necessitate materials that can withstand variable subsurface stresses resulting from high temperatures, thermal cycling, and rock strengths, as well as corrosive working fluids. As such, manufacturing with high-grade materials and specialized geometries can be necessary. However, the combined effects of low production volumes required to supply the existing U.S. geothermal market and the diminished lifetime of these tools due to the harsh conditions encountered in geothermal environments result in prohibitively high manufacturing costs.

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[7] Note that, in Section 2.1.3.4, "cross-cutting" refers to activities that have some combination of science and exploration techniques but apply to Exploration and Characterization specifically.

As a traditional GTO research pillar, geothermal tool RD&D has realized game-changing advancements across the application space for geothermal, such as the PDC bit (Gallaher et al. 2010). GTO efforts include a prize competition in collaboration with the DOE Advanced Manufacturing Office to integrate additive manufacturing approaches that can improve the design and performance of geothermal tools, components, and equipment. Additionally, novel coatings for downhole equipment and synthesis of new well-construction materials are all actively represented in the GTO research portfolio. Opportunity exists to continue leveraging these efforts as well as broader DOE investments in advanced manufacturing that are benefitting industries with shared challenges (e.g., oil and gas, clean energy, aerospace, automotive) to accelerate technology development and innovation across all geothermal energy resource types. Such research advancements also represent technology transfer opportunities with other subsurface energy applications, including oil and gas.

2.6.2.3 Technology Commercialization

GTO's primary mission is reducing the risk and costs associated with developing geothermal resources. Work is conducted in collaboration with a robust network of companies, entrepreneurs, academic researchers, and other vital stakeholders. These stakeholders represent the natural hand-off between programmatic basic research and broader commercial adoption of geothermal technologies. GTO actively supports commercialization efforts for both DOE-developed and industry-developed technologies through several financial mechanisms, including DOE's Small Business Innovation Research and Small Business Technology Transfer programs and DOE Technology Commercialization Fund awards. GTO supports geothermal-focused entrepreneurs through programs such as the Lab-Embedded Entrepreneurship Program. Where applicable, GTO also supports and funds demonstration activities. By testing and proving technology advances in the field, GTO-funded researchers can help provide real-world data and experience, thus reducing risk for geothermal developers to adopt enhancements or new technologies. GTO's collaborative work and demonstration help move technology commercialization forward across all geothermal applications and are crucial to the ultimate growth of geothermal energy.

2.6.2.4 Energy Transitions

Increasing coordination with the oil and gas sector can lead to important opportunities as the geothermal community focuses on integrating with the sector's infrastructure, workforce, and the unique skillsets. GTO and the broader geothermal community understand that this integration will not only accelerate geothermal deployment but will also encourage this sector's just transition into a renewable energy future.

According to the U.S. Energy Information Administration, there are nearly 1 million active oil and gas wells in the United States plus a vast number that are presently idle but not yet plugged and abandoned (U.S. Energy Information Administration 2020). Many of these wells access temperatures that can supply geothermal energy, including the co-production of low-enthalpy electricity generation and direct-use applications alongside oil and gas extraction. Utilization of idle wells for geothermal power or heat can eliminate their substantial methane emissions. Existing wells (in particular, abandoned or idle wells) and associated infrastructure also represent a significant capital investment that could be leveraged for development of geothermal resources. These assets could also be applied to thermal energy storage where development costs may be prohibitively high.

In addition to infrastructure, the oil and gas industry also has a large and highly skilled workforce—the skills and knowledge of which are applicable and transferable to the geothermal sector. Integrating the oil and gas workforce and their skills and knowledge into the geothermal community will result in highly trained oil and gas workers ready to focus on geothermal research, development, and operations. The replicability and reliability of oil and gas practices, employed at geothermal projects, can dramatically impact the economics of geothermal energy use and accelerate development of geothermal energy resources. Most importantly, oil and gas workers will benefit from secure and consistent job opportunities; the geothermal industry could offer as many as 250,000 jobs annually and $219 billion of cumulative economic impact annually by 2050 (Millstein et al. 2019).

Fluctuating economic conditions in the oil and gas industry and increased acceleration toward a clean energy economy open possible collaboration between the geothermal and oil and gas industries that can benefit both sectors and the nation. Engaging with the oil and gas industry and finding shared opportunities will be an important focus across GTO's research portfolio in the next five years.

2.6.2.5 Stakeholder Engagement, Communication, Education, and Outreach

Stakeholder engagement will be critical to fostering geothermal deployment. GTO's fundamental engagement goal is to develop relationships with and listen to individuals and communities, ascertain their goals and challenges, and empower them to explore how geothermal can impact their lives. Along the way, thorough and strategic communication and engagement activities can focus on the benefits and uses of geothermal energy as well as strategic socialization of the numerous opportunities offered by DOE and other entities for deploying geothermal via technical assistance, technology, and system development and deployment.

Geothermal energy is a renewable energy supplying benefits and advantages commensurate with those of solar, wind, water, bioenergy, and other renewable sources. Geothermal is also ubiquitous and diverse in presentation—on display in Yellowstone National Park; providing significant, firm, flexible clean energy generation for states including Nevada, California, and Hawaii; and harnessed in homes across the country with GHPs. Geothermal resources can provide clean energy throughout the nation and for a range of consumers—from small rural communities that need distributed power to urban centers with high energy demands and large populations. The national laboratories contain a deep bench of geothermal specialists, economists, and champions, and the GTO budget has grown steadily over the past decade to $110 million in FY 2021 appropriations. There are currently 2.6 GW of geothermal electricity production online in the United States that could reach 60 GW by 2050 with the right technology advancements. Also by 2050, 17,500 GDH systems and 28 million GHPs could be deployed nationwide.

Nevertheless, geothermal energy suffers from a broad lack of awareness. The geothermal community, along with GTO, assumes that this is due to geothermal energy's unique features, such as its subsurface nature and lack of surface manifestations, current geographic limitations, and low-profile infrastructure. Amongst stakeholders that are aware of geothermal energy, questions of geothermal's economic and technical feasibility, perceived risk of induced seismicity, volcanic hazards, and water use and contamination permeate.

To move beyond this paradigm, GTO and the geothermal community will work with communities and stakeholders to better understand how geothermal energy and infrastructure can provide meaningful community benefits and support both communities and the geothermal industry to develop best practices and projects that realize those benefits. Engagement activities include roundtables, interviews, and conversations with a representative array of current and potential geothermal stakeholders. The subsequent engagement and outreach campaign will likely include website and collateral development, partnerships with local and state nonprofits, and high impact relationship building for geothermal message procreation and a disperse advocacy network.

GTO will also continue to weave the priorities of energy equity, environmental justice, state and local collaboration, workforce development, and diversity in STEM throughout the programmatic portfolio and engagement and communication activities. Additionally, GTO will collaborate with other EERE and DOE technology offices on new Joint Office Partnerships, buttressing and supporting that work through innovative means within the Office.

3 Program Evaluations

3.1 Introduction

GTO takes an active approach to consistently assessing program activities and effectiveness. GTO's program evaluation activities ensure progress toward DOE, EERE, and GTO goals, while also ensuring effective stewardship of DOE investments and taxpayer dollars. GTO engages in informal and ongoing program evaluation through staff meetings, project check-in calls, brainstorming discussions, and other activities. In addition, GTO adheres to EERE guidelines for formal evaluations. These EERE guidelines are founded in two key objectives:

1. To assess whether planned technical goals were met and commercialization and market results achieved
2. To identify opportunities to make continuous improvements in programs in order to effectively and efficiently manage public investments.

Section 3.2 summarizes GTO's formal program evaluation activities.

3.2 Program Evaluation Activities

Program evaluation is a core GTO function. Regular evaluation activities help ensure progress toward research objectives, alignment with DOE and EERE goals, and effective public investment. Program evaluation activities also support GTO budget planning and decision making and provide independent analysis and external review recommendations as needed. GTO's primary evaluation activities are described in this section.

3.2.1 Merit Review and Competitive Project Selection

GTO-funded research projects that are submitted through an open and competitive proposal process undergo a comprehensive independent merit review by technology experts from industry, academia, and government. The application process may include multiple phases prior to development of a full application and features a process by which applicants may respond to reviewer comments. Each proposal is rated using evaluation criteria that emphasize the scientific and technical merit of the approach, potential energy and economic impacts, quality of the work plan, capabilities and resources of the applicant team, and other specific criteria. The use of evaluation criteria provides comparability and adherence to stated objectives.

The independent merit review process provides objectivity, transparency, and efficacy in project selection—ultimately ensuring effective use of GTO funding to support research objectives and priorities. This open, merit-based process also facilitates selection of optimal public-sector investments.

3.2.2 Ongoing Project and Portfolio Assessments

In addition to being subject to merit review and regular check-ins, GTO-funded projects are evaluated throughout execution. In-progress reviews include stage-gate reviews, go/no-go decisions, GPRA targets, and quarterly project milestones. These ongoing assessments occur at specified intervals that are negotiated as part of the project award phase. Stage-gate reviews and go/no-go decisions ensure that a project is meeting agreed-upon goals or technology advancements; if not, the project may be renegotiated or even canceled. GTO also monitors progress of awarded projects through regular project check-in meetings, peer review (Section 3.2.3), and other activities.

3.2.3 Peer Review

In adherence with EERE guidance, GTO uses an external peer review process to assess the performance of research activities and GTO as a whole. The peer review process may include a combination of technology area peer reviews, individual project peer reviews, and an overall office-level peer review. Through the peer review process, independent reviewers assess the GTO portfolio along a number of key metrics, including productivity, technical quality and accomplishments, relevance to GTO and EERE strategic and programmatic goals, and overall portfolio management.

For the peer review, technical experts from industry, academia, and government are selected as reviewers based on their experience and expertise in various aspects of geothermal energy. The reviewers score and provide qualitative comments based on the presentations and accompanying background information provided by principal investigators and GTO. Peer reviews are essential for obtaining regular, objective feedback on whether the GTO portfolio is balanced, impactful, and performing appropriately.

Results of the peer review are published in a public summary report, including GTO's response to peer review feedback and comments.

3.2.4 Impact Evaluations

In some cases, GTO uses impact evaluations conducted by independent external experts to quantify research-attributed outcomes for geothermal. As defined by EERE, such outcomes may include economic performance (e.g., return on investment), knowledge diffusion (e.g., measured via various patent citation metrics), market effects (e.g., changes in the scale-up of supply and distribution chains, consumer awareness, and adoption decision practices), and benefit-cost assessments.[8]

3.2.5 Multi-Year Program Plan Updates

The results of evaluation activities can play an important role in helping GTO determine whether its investments are achieving Strategic Goals as well as leading to impactful energy, economic, environmental, and energy security benefits. While the MYPP guides the research portfolio, results of portfolio assessment in turn inform the MYPP. If portfolio performance is deemed not to be meeting GTO's Strategic Goals and advancing geothermal, the MYPP may be adjusted to better direct future RD&D.

In addition, the energy sector is rapidly evolving and constantly responding to ever-changing domestic and global conditions. These changes can have significant effect on the energy needs of the American public and the solutions required to meet those needs. As such, the GTO MYPP is intended to be updated and adapted in response to the market. Regular reviews and updates will continually assess GTO's research and its ability to contribute to U.S. demands for secure, reliable, diverse, and affordable energy.

The initial goal is to revisit the MYPP in FY 2024 to determine whether the plan is meeting GTO performance goals and helping to address U.S. energy demands.

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[8] https://www.energy.gov/eere/analysis/types-evaluations#impact

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