

GEO



VISION

Harnessing the Heat Beneath Our Feet



U.S. DEPARTMENT OF
ENERGY



Sunset over a U.S. Department of Energy geothermal test site (Naval Air Station Fallon in Nevada).

Photo credit: Dick Benoit

Foreword

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Letter from the Director

The Earth beneath our feet contains vast energy potential, enough to power the global electric grid many times over. This natural geothermal heat radiating from the Earth's mantle—a byproduct of our solar system's formation billions of years ago—is virtually limitless in supply. Over the past century, geothermal researchers and operators have worked to harness this resource. Geothermal is an increasingly valuable contributor to energy diversity—and for good reason: it's an “always-on,” renewable, 50-state solution that can provide flexible electricity and heating and cooling solutions to all Americans.



To grow as a national solution, geothermal must overcome significant technical and non-technical barriers in order to reduce cost and risk. The subsurface exploration required for geothermal energy is foremost among these barriers, given the expense, complexity, and risk of such activities. Early-stage research into technology improvements can help reduce development costs and improve exploration and production, all of which are essential to achieving geothermal's full potential. Realizing this potential will, in turn, drive investment in America's energy diversity. The status of geothermal energy mirrors the oil and gas industry at a time when unconventional oil and gas reserves were known, but the technology did not exist to produce them economically. Through research and collaboration, the oil and gas industry was able to tackle those barriers and attain access to previously untapped resources.

To evaluate similar opportunities for the success of geothermal energy, the U.S. Department of Energy's Geothermal Technologies Office (GTO) initiated the *GeoVision* analysis. This rigorous technical analysis evaluated future geothermal deployment opportunities based on three core objectives:

- Increased access to geothermal resources
- Reduced costs and improved economics for geothermal projects
- Improved education and outreach about geothermal energy through stakeholder collaboration.

The *GeoVision* analysis concludes that meeting all three of these objectives can result in a sizable increase in America's use of geothermal energy. Analysis results show that, with technology improvements, geothermal power generation could increase nearly 26-fold from today—representing 60 gigawatts of installed capacity by 2050. This capacity is paired with tremendous potential for using geothermal energy for heating and cooling: *GeoVision* analysis models indicate the opportunity for more than 17,500 district-heating installations as well as heating and cooling for the equivalent of more than 28 million households using geothermal heat pumps by 2050. Achieving the deployment levels in the *GeoVision* analysis can also deliver substantial value to all Americans by contributing to the long-term portfolio of affordable energy options and providing environmental benefits. Through increased geothermal deployment, America could realize a stronger geothermal energy sector, a more stable power grid, and economic and environmental benefits.

In the pages that follow, you will gain insight into more than just detailed analyses; this report shows us how to move the geothermal dial from what we know exists to what we envision is possible over the next 30 years. The *GeoVision* analysis takes us beyond a declaration of resource potential by illustrating what is real today and painting a picture of what could be real tomorrow.

How the geothermal stakeholder community chooses to impact that reality is fully in our hands. The comprehensive Roadmap presented in this report forms a call for broad stakeholder action across the geothermal community. Through collaboration, we can move toward a common goal of realizing the *GeoVision* deployment levels and the associated benefits to the nation.

The *GeoVision* report reflects a multiyear effort with contributors from industry, academia, national laboratories, and federal agencies. A total of 20 independent experts vetted each step of the analytic process, and a group of more than 40 reviewers representing the domestic and international stakeholder community appraised and commented on the report draft. All participants in this process were instrumental in documenting the state of the industry. On behalf of everyone at GTO, I offer my sincerest thanks to each of you involved in building this view into the future of geothermal energy.

Best regards,

Dr. Susan G. Hamm
Director, Geothermal Technologies Office
U.S. Department of Energy

Introduction

Energy is the heartbeat of America. It touches nearly everything we do every day—from life at home; to work and communication; to critical infrastructure that saves lives in hospitals, strengthens our national security, and transports us to new places. Some of the most vital questions for the United States in the 21st century focus on energy, including: Where will we get our energy, and how can we build secure, reliable, and resilient systems that accommodate a changing energy mix? How do we protect U.S. energy interests and innovation while participating in a global economy? Which energy solutions ensure economic and environmental vitality today and into the future?

Geothermal energy provides an answer to many of these essential questions. The “heat beneath our feet” is an always-on source of secure, reliable, and flexible domestic energy that can be utilized across industrial, commercial, and residential sectors. The use of geothermal energy also offers important benefits to the nation, including grid stability, greater diversity in the portfolio of affordable energy options, efficient heating and cooling, and reduced air pollution.

Despite the benefits of geothermal energy and its ability to meet some of the nation’s most pressing energy needs, the United States has tapped only a fraction of its abundant geothermal resources. Harnessing the full potential of U.S. geothermal resources will strengthen domestic energy security and allow the United States to continue its leadership in energy innovation.

To examine this potential for geothermal resources to play a key role in the nation’s energy future, the U.S. Department of Energy (DOE) initiated the *GeoVision* analysis. The analysis is based on rigorous modeling and simulation that enabled a team of experts to assess the state of geothermal energy, quantify growth opportunities and associated impacts on the nation, and formulate actions to increase geothermal deployment.

This report, *GeoVision: Harnessing the Heat Beneath Our Feet*, summarizes the analyses and discusses the many opportunities that geothermal energy offers in both electric and non-electric uses. The report also highlights the outcomes the United States could realize from increased geothermal deployment and outlines a range of activities necessary to reach this deployment. The goal is to provide a glimpse into the abundant possibilities that geothermal energy has to offer the nation and to highlight some of the steps needed to increase geothermal deployment. The full body of analytical work is detailed in the *GeoVision* Analysis Supporting Task Force Reports, as listed in the references section. Not all assumptions, results, and scenarios used in the analysis are contained within this report.

The *GeoVision* report is organized as follows:

Executive Summary	High-level summary of the <i>GeoVision</i> analysis and highlights of key findings
Chapter 1: Developing the <i>GeoVision</i>	Overview of the <i>GeoVision</i> analysis, approach, and findings
Chapter 2: What is Geothermal Energy?	Brief description of geothermal energy, including electric and non-electric applications in the United States, and barriers to growth
Chapter 3: <i>GeoVision</i> Analysis: Models and Scenarios	Summary of the <i>GeoVision</i> analysis, models, and scenarios
Chapter 4: <i>GeoVision</i> Analysis: Results, Opportunities, and Impacts	Results of the <i>GeoVision</i> analysis, including U.S. deployment potential for electric and non-electric uses of geothermal energy and discussion of the potential for geothermal energy to contribute energy diversity and environmental benefits to the nation
Chapter 5: The <i>GeoVision</i> Roadmap: A Pathway Forward	Roadmap of actions that, if taken, could support growth in the use and application of geothermal energy in the United States
Appendix A	Acronyms
Appendix B	Glossary
Appendix C	Detailed Modeling Assumptions and Results
Appendix D	Contributors



Geothermal drilling rig near a U.S. Department of Energy test site (Naval Air Station Fallon in Nevada).
Photo credit: Lauren Boyd/U.S. Department of Energy

Executive Summary

Geothermal is America's untapped energy giant.

Geothermal energy is a renewable and diverse solution for the United States—providing reliable and flexible electricity generation and delivering unique technology solutions to America's heating and cooling demands. Geothermal resources can be found nationwide, are “always on,” and represent vast domestic energy potential. Only a fraction of this potential has been realized due to technical and non-technical barriers that constrain industry growth.

The U.S. Department of Energy's (DOE's) Geothermal Technologies Office (GTO) engaged in a multiyear research collaboration among national laboratories, industry experts, and academia to identify a vision for growth of the domestic geothermal industry across a range of geothermal energy types. The effort assessed opportunities to expand geothermal energy deployment by improving technologies, reducing costs, and mitigating barriers. The analysis also assessed the economic benefits to the U.S. geothermal industry and the potential environmental impacts of increased deployment—including jobs, consumer energy prices, water use, and air quality—and investigated opportunities for desalination, mineral recovery, and hybridization with other energy technologies for greater efficiencies and lower costs.

The *GeoVision* analysis culminated in this report, *GeoVision: Harnessing the Heat Beneath Our Feet*. In addition to summarizing analytical results about geothermal energy opportunities, the report includes a Roadmap of actionable items that can achieve the

outcomes of the analysis. The *GeoVision* Roadmap is a comprehensive call to action to encourage and guide stakeholders toward the shared goal of realizing the deployment levels and resulting benefits identified in the *GeoVision* analysis.

The *GeoVision* analysis demonstrates the unique characteristics of geothermal energy and its unrealized potential, including:

- Constant and secure renewable electric power generation with flexible and load-following capabilities that provide essential services contributing to grid stability and resiliency
- Nationwide energy applications through unique capabilities in electricity generation, as well as residential, commercial, and district heating and cooling
- Commercial technologies that are ready to deploy, augmented by developing technologies with vast potential for increased electricity generation and direct-use applications
- Job impacts in both the manufacturing and geothermal sectors
- Revenue potential for federal, state, and local stakeholders, as well as royalty potential for leaseholders.

The *GeoVision* analysis used a suite of modeling tools and scenarios to evaluate the performance of geothermal technologies relative to other energy technologies. The analyses included evaluating the

potential role of existing and future geothermal deployment in both the electric sector and the heating and cooling sector. In the electric sector, the analysis considered existing conventional (hydrothermal) geothermal resources as well as unconventional geothermal resources,¹ such as enhanced geothermal systems, or EGS. In the heating and cooling sector, the analysis modeled geothermal heat pumps (GHPs, which are also known as ground-source heat pumps)² and district-heating systems (using both conventional and EGS resources).

By evaluating scenarios for increased deployment of geothermal energy, the *GeoVision* analysis provides a foundation to maintain and advance the nation's position as a leader in geothermal energy applications and technology innovation. The models used prevailing and potential future technology assumptions under existing and proposed state and federal policy scenarios. The analysis does not assume or create any previously un-introduced policies; it considers only policies that are in force or have been introduced.

Key findings of the *GeoVision* analysis:

Technology improvements could reduce costs and increase geothermal electric power deployment.

Improving the tools, technologies, and methodologies used to explore, discover, access, and manage geothermal resources would reduce costs and risks associated with geothermal developments. These reductions could increase geothermal power generation nearly 26-fold from today, representing **60 gigawatts-electric (GW_e)**³ of always-on, flexible electricity-generation capacity by 2050. This capacity makes up 3.7% of total U.S. installed capacity in 2050, and it generates 8.5% of all U.S. electricity generation. Technology improvements are on the critical path toward achieving commercial EGS. This is vital because the *GeoVision* analysis demonstrates that, relative to

The *GeoVision* analysis provides a comprehensive assessment of the state of geothermal energy and identifies deployment opportunities and pathways for targeted action that could achieve a shared vision for industry growth.

other geothermal resources, EGS resources have the potential to provide the most growth in the electric sector. EGS can also support significant growth within the non-electric sector for district heating and other direct-use applications.

Optimizing permitting timelines could reduce costs and facilitate geothermal project development, potentially doubling installed geothermal capacity by 2050.

The *GeoVision* analysis included the examination of key regulatory, permitting, and land-access barriers to geothermal development. Streamlined regulations and permitting requirements can be achieved through a variety of mechanisms to shorten development timelines, which can—in turn—reduce financing costs during construction. For example, the analysis showed that placing geothermal regulatory and permitting requirements on a level similar to that of oil and gas and other energy industries could allow the geothermal industry to discover and develop additional resources and to reduce costs. The *GeoVision* analysis demonstrated that optimizing permitting alone could increase installed geothermal electricity-generation capacity to **13 GW_e** by 2050—more than double the 6 GW_e projected in the Business-as-Usual scenario that serves as the baseline for the *GeoVision* analysis.

Overcoming barriers to geothermal heating and cooling could stimulate market growth.

Geothermal heating and cooling is an underutilized

1 Conventional geothermal resources refer to naturally occurring hydrothermal resources developed using existing technologies (the term “hydrothermal” refers to the combination of water [hydro] and heat [thermal]). Unconventional geothermal resources refer to a class of resources that will require the development of new and innovative technologies to enable economic resource capture. Enhanced geothermal systems, or EGS, are the most significant of the unconventional geothermal resources and are characterized by the presence of a thermal energy source in the Earth's crust that lacks the permeability and/or groundwater necessary for economic energy recovery. These resource characteristics are elaborated in Chapter 2.

2 Heat-pump technologies, which use the thermal properties of the shallow earth to provide renewable and efficient geothermal heating and cooling, are commonly referred to by two different names: geothermal heat pumps, and ground-source heat pumps. The DOE has traditionally referred to this technology and industry as “geothermal heat pumps,” and the Internal Revenue Service federal statutes—as well as state renewable portfolio standards that recognize geothermal technology as eligible—have done so historically on the basis of the specific terminology, “geothermal heat pumps.” The *GeoVision* analysis uses the term geothermal heat pumps, while acknowledging that some stakeholders, e.g., the International Ground Source Heat Pump Association and the European Union, have started to adopt the name “ground-source heat pumps” to describe the technology and industry.

3 GW_e = gigawatts-electric, which is power available in the form of electricity—in the case of geothermal, converted from heat energy in the Earth. The *GeoVision* analysis also considers gigawatts-thermal (GW_{th}) for direct-use and GHP applications. GW_{th} is the power available directly from heat or thermal energy. In GHP applications, GW_{th} is the heating/cooling capacity of the system itself; for direct-use applications, GW_{th} refers to the heating capacity that is extracted directly from the geothermal heat in the ground and delivered to the direct-use application.

resource for U.S. homes and businesses and an area of key growth potential. The GHP industry is expected to reduce energy costs to residential and commercial consumers and provide greater reliability and consistency in heating and cooling options. The existing installed capacity is about 16.8 gigawatts-thermal (GW_{th}) (Lund and Boyd 2016) and is equivalent to GHP installations in about 2 million households. The *GeoVision* analysis determined that the market potential⁴ for GHP technologies in the residential sector is equivalent to supplying heating and cooling solutions to 28 million households, or **14 times greater** than the existing installed capacity. This potential represents about 23% of the total residential heating and cooling market share by 2050. Similarly, the economic potential for district-heating systems using existing direct-use geothermal resources combined with EGS technology advances is **more than 17,500 installations nationwide**, compared to the 21 total district-heating systems installed in the United States as of 2017 (Snyder et al. 2017). These district-heating installations could satisfy the demand of about 45 million households (EIA 2015; McCabe et al. 2019; Liu et al. 2019). Realizing direct-use, district-heating potential will require advancing EGS technology and reducing soft-cost⁵ barriers.

Geothermal energy offers economic development opportunities in both rural communities and urban centers across the United States.

The results of the *GeoVision* analysis indicate that taking action consistent with the associated *GeoVision* Roadmap could expand the domestic geothermal industry and potentially add job opportunities in both urban and rural communities. Development of a robust residential and commercial GHP industry could also expand the U.S. geothermal workforce.⁶

Increased geothermal deployment could improve U.S. air quality and reduce CO₂ emissions.

The *GeoVision* analysis indicates opportunities for improved air quality resulting from reductions in sulfur dioxide (SO_2), nitrogen oxides (NO_x), and fine particulate matter ($\text{PM}_{2.5}$) emissions. The analysis further identifies opportunities for reduced

carbon-dioxide emissions. For the electric sector, this could cumulatively result in up to 516 million metric tons (MMT) of avoided carbon-dioxide equivalent (CO_2e) emissions through 2050. For the heating and cooling sector, impacts through 2050 could cumulatively include up to 1,281 MMT of CO_2e emissions avoided. By 2050, the combined CO_2e reductions for the two sectors is equivalent to removing about 26 million cars from the road annually.

The geothermal deployment levels calculated in the *GeoVision* analysis could be achieved without significant impacts on the nation's water resources.

Compared to the Business-as-Usual scenario, the high levels of deployment evaluated in the *GeoVision* analysis result in a slight increase (-4%) in the amount of water consumed by the power sector in 2050. This increase in consumption can be mitigated through the use of non-freshwater resources such as municipal wastewater and brackish groundwater.

Geothermal energy is secure, reliable, flexible, and constant. It offers the United States a renewable source for power generation as well as heating and cooling of homes and businesses. Geothermal resources and technologies are primed for strong deployment growth and stand ready to provide solutions to meet America's 21st-century demands for energy security, grid stability and reliability, and domestic and commercial heating and cooling needs.

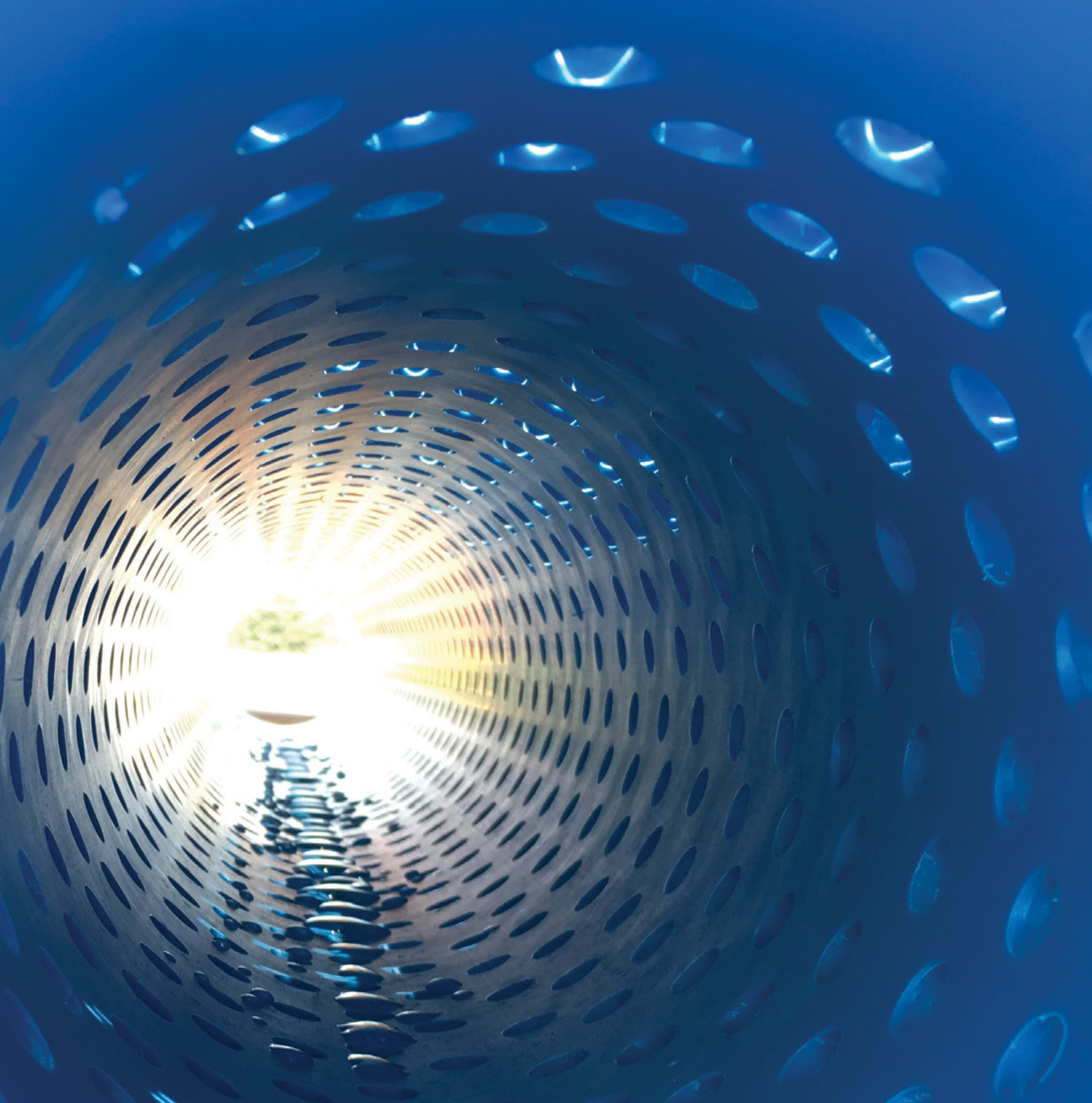


Workers on a drilling rig at The Geysers geothermal field in California.
Photo credit: Robert Hopkins

⁴ The market potential of a renewable resource is defined broadly as the portion of technical potential that is likely to be deployed considering the technical viability of the project and the reaction of consumers in the market to economic factors (Sigrin et al. 2016, McCabe et al. 2019). See Figure 3-1.

⁵ Soft costs are non-construction costs incurred before project commissioning, including (among other things): public perception/educating the public, utilities, regulators, and policymakers; risk; financing; permitting; legal fees; insurance; workforce availability and training (including installers and small drillers); political support, e.g., policies, political terms, and regional resources; power purchase agreements; and attracting large players (oil and gas companies).

⁶ A task force report supporting the *GeoVision* analysis assessed gross job impacts from geothermal deployment compared with business-as-usual scenarios (Millstein et al. 2019). These gross job impacts represent total jobs needed to fulfill increased geothermal deployment. Because those jobs may displace other energy-generation technologies and do not represent the net impact of geothermal jobs on employment within those other sectors, they are not discussed or quantified here. Assessing net job impacts was beyond the scope of the *GeoVision* analysis. Refer to Millstein et al. 2019 for more details about gross jobs impacts.



CHAPTER ONE

Developing the *GeoVision*

View inside a condenser at a geothermal combined heat and power plant.

Photo credit: Viktor Hava

1 Developing the *GeoVision*

The *GeoVision* analysis assessed the domestic geothermal industry across numerous resource types and technology applications, within the context of technical and non-technical barriers and improvements as well as economic benefits to the geothermal industry and environmental impacts to the nation. The analysis quantified geothermal deployment that could be achievable under a range of potential scenarios and assessed economic benefits to the geothermal industry and environmental impacts resulting from increased geothermal energy on the U.S. grid and in U.S. homes and businesses. The *GeoVision* analysis examined electricity generation as well as heating and cooling applications and evaluated the impact of additional value streams that could help balance the costs of developing a geothermal resource. The results of the *GeoVision* analysis confirm the potential for geothermal to be an essential part of the nation's critical energy infrastructure.

Several aspects of geothermal make it unique among energy resources. Geothermal energy resources are available in vast quantities—on a nationwide geographic scale—and can be used in a range of applications, including electric power generation and heating and cooling of homes and businesses. Geothermal energy can provide flexibility to the grid through ancillary services that help respond to changes in electrical load and support reliable grid operation. As an onsite subsurface resource with around-the-clock availability, geothermal energy offers increased energy security compared to other generation technologies.

The geothermal industry has long been aware of the benefits of and challenges to increased geothermal deployment—that is, sourcing more of the nation's energy needs from geothermal resources. However, until the landmark effort of the *GeoVision* analysis,

geothermal deployment potential had never been quantified at a national scale or across a broad range of technology applications. The *GeoVision* analysis achieves these objectives, with the results providing a case for the potentially sizable role that geothermal resources could play in meeting the nation's 21st-century energy demands.

The *GeoVision* analysis addresses gaps in understanding of the potential of geothermal resources and provides a case for geothermal energy to have a sizable role in meeting the nation's 21st-century energy demands. The results of the *GeoVision* analysis confirm the opportunities for geothermal to be an essential part of the U.S. energy infrastructure.

The *GeoVision* analysis mirrors much of the methodology and reporting methods used in the U.S. Department of Energy's (DOE's) *SunShot Vision Study* (DOE 2012), *Wind Vision* (DOE 2015), and *Hydropower Vision* (DOE 2016a).⁷ The *GeoVision* analysis included the state of the art in conventional geothermal electricity generation and geothermal heating and cooling applications. The analysis considered resources and technologies under development, including enhanced geothermal systems (EGS), low-temperature and sedimentary geothermal resources, hybridized geothermal applications, and others.

The *GeoVision* analysis followed a “bottom-up” approach to answering a fundamental question about the levels of deployment possible under varied scenarios:

⁷ DOE's *Vision* studies for solar energy, wind energy, and hydropower can be found at the following respective URLs: *SunShot Vision Study* (<https://energy.gov/eere/solar/sunshot-vision-study>); *Wind Vision* (<https://energy.gov/eere/wind/wind-vision>); and *Hydropower Vision* (<https://energy.gov/eere/water/articles/hydropower-vision-new-chapter-america-s-1st-renewable-electricity-source>).

“On the basis of detailed assessments of the geothermal industry, barriers to deployment, and both existing and improved technologies, what level of deployment would be achievable and what would be the corresponding economic benefits to the industry and the environmental impacts of those deployment levels on the United States?”

To address this question, the DOE’s Geothermal Technologies Office (GTO) led an analysis of geothermal energy growth scenarios through 2050. The analysis aimed to execute five key activities (Richard et al. 2016):

1. Define and evaluate geothermal growth scenarios through 2050, backed by robust data, modeling, and analysis
2. Address all major geothermal resource and market segments, i.e., existing and potential hydrothermal and EGS resources, electric and non-electric technology applications, and other additive value streams
3. Execute an objective and transparent process, supported by peer-reviewed industry data that are made available to decision makers
4. Produce a vision for domestic geothermal industry growth that is aspirational, motivating, and achievable
5. Articulate strategies for growth and identify paths by which the industry and its stakeholders may achieve the results identified in the *GeoVision* analysis.

1.1 *GeoVision* Analysis Approach

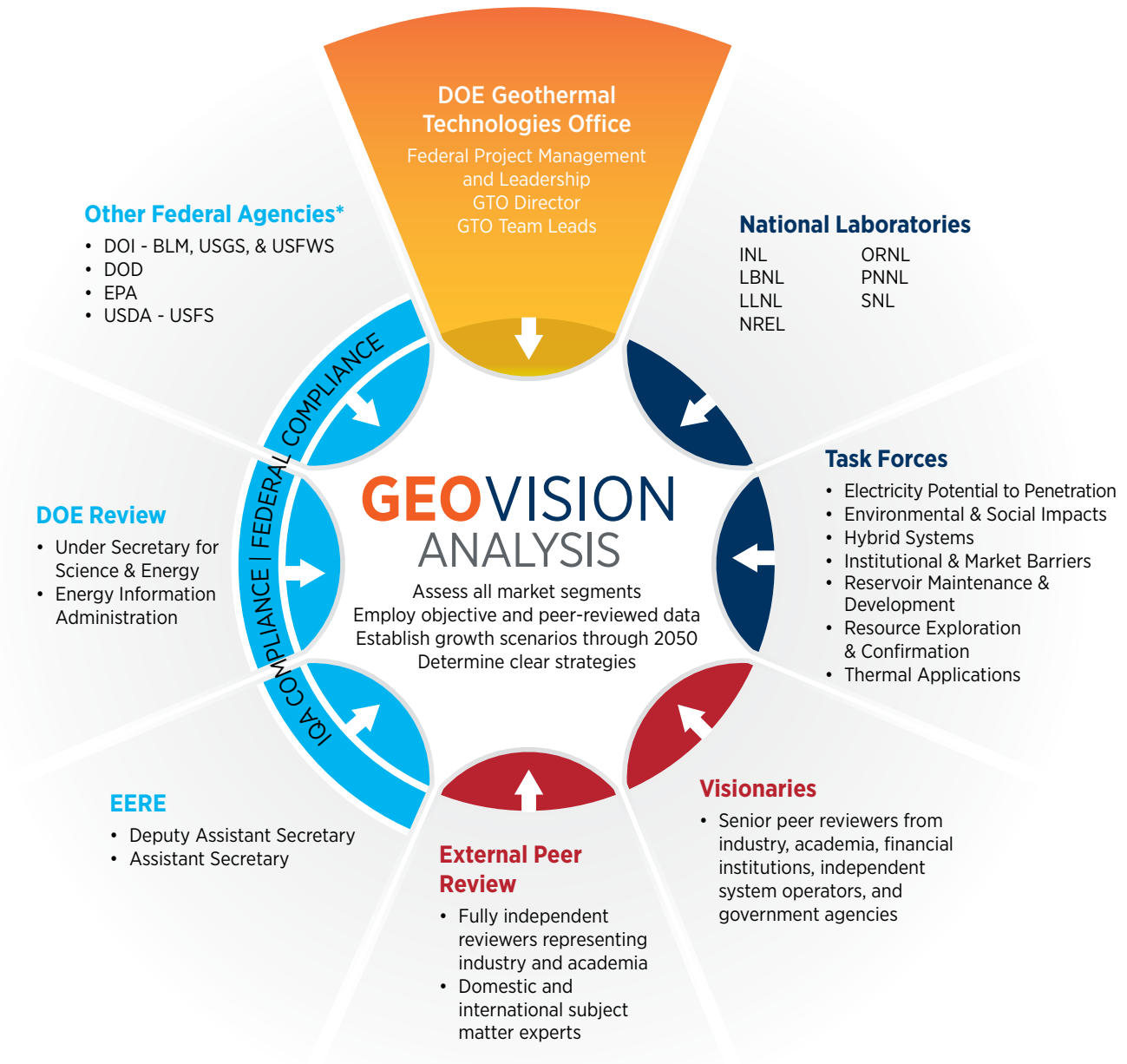
The *GeoVision* analysis relied on the collection, modeling, and assessment of robust datasets through DOE national laboratory partners. The analysis was executed as a broad collaborative effort, following a process that included 20 industry peers (known

as “Visionaries”) and a diverse group of more than 40 expert reviewers from federal, state, and tribal government agencies, as well as geothermal companies, environmental organizations, academic institutions, electric power system operators, research institutions, and other non-governmental stakeholder groups (Appendix D). Engaging a broad range of stakeholders ensured objectivity and transparency.⁸ Collectively, participants in the *GeoVision* analysis were instrumental in documenting the state of the industry and identifying future opportunities for growth, as well as pinpointing challenges that need to be addressed so that the geothermal industry can continue to evolve and contribute value to the nation. The framework for the *GeoVision* analysis and associated collaborative effort is illustrated in Figure 1-1, including compliance with guidance issued by the Office of Management and Budget as authorized by the Information Quality Act, or IQA.



Aerial drone view of geothermal drilling operations near Klamath Falls, Oregon. Photo credit: Kevin P. Graham

⁸ The Office of Management and Budget’s “Final Information Quality Bulletin” provides guidelines for properly managing peer review at federal agencies in compliance with Section 515(a) of the Information Quality Act (Pub. L. No. 106-554). GTO followed these guidelines in conducting the *GeoVision* analysis.



*Other Federal Agencies: Department of Interior, Bureau of Land Management, United States Geological Survey, United States Fish and Wildlife Service, Department of Defense, Environmental Protection Agency, United States Department of Agriculture, and United States Forest Service

Note: National laboratories are defined in Appendix A.

Figure 1-1. Framework of the interaction of parties involved in the formation and execution of the *GeoVision* analysis

Figure Note: DOE's GTO provided a governance and leadership role for the GeoVision analysis by integrating the technical task force work products, guiding the formation of the GeoVision objectives, and leading the external and interagency review process. Technical task forces of national laboratory partners worked with GTO task management to produce the foundational work products that are the basis of the GeoVision analysis. This work was iteratively and transparently reviewed by a group of industry peers ("Visionaries"), as well as by a diverse group of expert external reviewers from federal, state, and tribal government agencies, and by geothermal companies, environmental organizations, academic institutions, electric power system operators, research institutions, and other non-governmental stakeholder groups.

The *GeoVision* analysis aimed to identify potential actionable pathways for expanding the use of geothermal technologies as cost-effective, reliable, and flexible contributors to a diverse, domestic energy portfolio. Achieving this goal can help expand the domestic geothermal industry and increase the nation's energy security through greater energy resource diversification. The *GeoVision* analysis was built on a structural framework of overarching objectives (Section 1.2). This framework facilitates the definition of action and sub-action areas that comprise a technical and institutional Roadmap (Chapter 5) designed to achieve the outcomes of the *GeoVision* analysis. The Roadmap forms the basis of a broad call to action to engage stakeholders toward realizing geothermal deployment levels identified in the *GeoVision* analysis and the potential resulting benefits to the nation.

1.2 Objectives of the *GeoVision* Analysis

As noted, DOE conducted the *GeoVision* analysis to assess the potential for increased geothermal deployment under varying technology and market scenarios. The goal of the *GeoVision* analysis is to enable stakeholders to harness the potential of geothermal energy and, ultimately, increase value for the nation. This value can be realized through domestic energy affordability and security, a more competitive geothermal industry, manufacturing opportunities, energy diversity, enhanced grid stability, and reduced water withdrawals and air emissions.

The *GeoVision* analysis was founded on the knowledge that increased geothermal deployment requires identifying and better managing risks and costs associated with development. As such, the analysis was based on three overarching objectives essential to reducing risks and costs. Addressing the aspects within each objective can facilitate the growth potential identified by the *GeoVision* analysis.

The first key objective on which the *GeoVision* analysis is based is **increasing access to geothermal resources**. The *GeoVision* analysis assessed three types of geothermal resources (Section 2.1): hydrothermal, EGS (unconventional), and geothermal heat pumps. The ability to locate, characterize, and access these

resources is fundamental to geothermal development. Geothermal resources are situated at varying depths and locations, so different technologies are used to access each type. Some of these technologies are existing and proven, whereas others are new or evolving. Because of differences in technology maturity, geothermal resource classes vary in degrees of risk and types of barriers. The *GeoVision* analysis considered opportunities that might be realized if geothermal stakeholders can overcome risks and barriers, thus enabling easier and more cost-effective resource access.

The *GeoVision* analysis identifies opportunities to expand the use of geothermal technologies as cost-effective, reliable, and flexible contributors to a diverse U.S. energy portfolio, thus helping to expand the domestic geothermal industry and increase energy security through greater energy resource diversification.

The second key objective is **reducing costs and improving economics for geothermal projects**.

Geothermal projects are often characterized by high upfront costs and long development timelines that lead to protracted investment payback periods relative to many other utility-scale power generation projects. These factors create risk for developers, tying up capital for long periods of time and making it difficult to obtain cost-effective financing. Risks can be even higher for projects that require unproven technologies to harness the geothermal resource and turn it into useful energy. Lowering development costs and improving overall project economics can reduce developer risk and improve the value of geothermal projects for financiers.

The goal of the *GeoVision* analysis is to enable stakeholders to harness the potential of geothermal energy and, ultimately, increase value for the nation.

The third key objective is **improving education and outreach about geothermal energy**. Unlike the sun or the wind, geothermal energy resources are located underground and are not commonly visible or tangible. Geothermal energy infrastructure also tends to have a lower profile and smaller footprint than other energy-generation facilities. Given these attributes, geothermal energy is not generally understood or appreciated by the public in the same way as other renewable energy resources such as solar and wind. Stakeholders can collaborate to create effective and accessible educational tools that help increase acceptance and interest—in turn, potentially influencing financing options, land access, and other aspects of geothermal development.

The foundational objectives of the *GeoVision* analysis are closely intertwined. Activities under each objective can occur simultaneously and will influence the other objectives; for example, reducing costs and improving education (second and third objectives) can help improve access to geothermal resources (first objective). Achieving the foundational objectives can reduce risk and costs for geothermal developers, increase growth potential for geothermal energy, and ultimately provide the United States with secure, flexible energy that offers economic benefits to the geothermal industry and environmental benefits nationwide.



A stationary blade casing for a geothermal steam turbine.
Photo credit: Sarah Pistone

1.3 Risk, Costs, and the *GeoVision* Analysis

As noted in Section 1.2, risk management and cost reduction are pivotal to increasing opportunities for geothermal energy. As discussed, each of the key objectives underlying the *GeoVision* analysis includes multiple concepts and activities that must be addressed to realize levels of deployment identified by the analysis. This section hones in on a few key barriers to geothermal growth, particularly as they relate to risk and cost in geothermal development.

Financing and Costs

In the electric sector, geothermal power projects have higher capital and financing costs than many other energy projects. Conventional geothermal developments have capital costs of about \$3,000 to \$6,000 per kilowatt-electric (kW_e), as compared to land-based wind or utility-scale solar photovoltaic capital costs, which are \$1,700 to \$2,100/kW_e (Cole et al. 2016).⁹ Additionally, finance data show that investors require a higher expected investment return for geothermal projects compared to other renewable power projects (Mendelsohn and Hubbell 2012), translating to higher financing costs (Wall et al. 2017). Reducing both capital and financing costs can help make geothermal power generation more competitive.

Financing disparities overlap the three key objectives of the *GeoVision* analysis. Challenges arise from the risk and cost of characterizing and quantifying subsurface resources, coupled with long construction timelines and financing terms that delay investment payback. In the test-drilling stage of a geothermal project, resource-confirmation activities and financing tend to carry high risk and high cost; at this stage, developers (and, hence, financiers) cannot be certain that a geothermal resource will provide a return on investment. Risks and costs vary for different types of geothermal resources, generally increasing with depth and temperature. Resource-confirmation activities also carry non-technical risks, such as uncertainties associated with project permitting

⁹ Capital costs vary by resource grade and power-plant configuration. Conventional geothermal power-plant developments consider hydrothermal flash and binary power plants, which have capital expenditures, or CAPEX, of \$5,049 and \$6,042/kW_e, respectively. Land-based wind developments have CAPEX ranging from \$1,737 to \$2,109/kW_e for resource grades from techno-resource group (TRG) 1 to TRG 10, respectively. Utility-scale solar photovoltaic CAPEX is \$2,024/kW_e. All data are from the 2016 Annual Technology Baseline (National Renewable Energy Laboratory 2016).

or land access. Financing becomes available at lower interest rates in the later drilling and construction phases of the project (Glacier Partners 2009, Wall et al. 2017, Doughty et al. 2018). Project risk decreases as production drilling ensues and the resource is proven to have commercial potential.

Industry Size and Technology Maturity

The risks and challenges encountered while drilling deep, high-temperature geothermal wells are broadly similar to those in the oil and gas industry, although the industries are vastly different in scale.¹⁰ Oil and gas companies are accustomed to subsurface and drilling risks, and, as such, know how to manage and reduce them. Oil and gas companies also tend to be well-capitalized and have successfully leveraged new technologies and improved business standards to minimize resource risks and costs (Text Box 1-1). In the geothermal industry, drilling risks and costs can be managed through similar approaches, but the comparatively small size of the industry presents challenges in gaining sufficient momentum to achieve similar results. Developing new technologies and business practices will also be necessary for the geothermal industry to manage risks unique to geothermal resources. Analysis related to drilling risks, technologies, and improvements for geothermal exploration and project development is available in Doughty et al. 2018 and Lowry et al. 2017. Addressing challenges related to drilling and other technologies is an important facet of the first two objectives of the *GeoVision* analysis.

Development Timelines

As noted in the second objective for the *GeoVision* analysis, the geothermal industry faces risks related to long development timelines (typically 7–10 years) that delay payback on initial investments and increase project financing costs. The *GeoVision* analysis evaluated potential scenarios for shortened development timeframes for geothermal electric projects. These scenarios include the effects of streamlined regulatory processes that would allow for faster and less costly drilling and testing of resource-confirmation wells (Young et al. 2019).¹¹ Such improvements could help reduce financing costs and improve project economics (second objective). In the geothermal district heating and GHP markets, risks are more closely related to lengthy payback periods; a lack of viable project financing models; and a lack of consumer education, awareness, and outreach (third objective).



Travertine deposits from an active geothermal hot spring forming a natural dam across the Jemez River in New Mexico.
Photo credit: James Lovekin

¹⁰ In 2016, oil and gas operators in the United States—supported by a \$48 billion oil field service industry—were estimated to have collectively drilled 151,481,900 feet in as many as 14,632 wells (WorldOil 2017, Grand View Research 2018). Accurate data on total annual domestic geothermal wells drilled are unavailable. However, by comparison to oil and gas, the relatively small size of the geothermal industry is illustrated by comparing the 860 total geothermal wells in the state of California (which has the world's largest installed capacity of geothermal power generation) to the 892 oil and gas wells drilled in California in 2017 alone (WorldOil 2017, State of California 2018).

¹¹ The *GeoVision* analysis considered multiple pathways for streamlined permitting and regulations. These pathways, which are summarized in Section 2.4 and elaborated in Young et al. 2019, include timeline reductions resulting from potential geothermal categorical exclusions. A categorical exclusion is “a category of actions which do not individually or cumulatively have a significant effect on the human environment and which have been found to have no such effect in procedure adopted by a Federal agency in implementation of these regulations (§ 1507.3) and for which, therefore, neither an environmental assessment nor an environmental impact statement is required” (40 CFR 1508.4). In the *GeoVision* analysis, the Improved Regulatory Timeline scenario assumed shortened development timelines. Potential regulatory-related scenarios for such timeframes include centralized permitting offices and a categorical exclusion that would allow drilling and testing of confirmation wells—consistent with the general parameters established for oil and gas in section 390 of the Energy Policy Act of 2005 (EPA 2005) and as proposed for the geothermal industry in section 3012 of S. 1460, the Energy and Natural Resources Act of 2017 (115th Congress)—to prove out a reservoir and allow for project financing for the remainder of the project. Exploring the details of such a categorical exclusion was outside of the scope of the *GeoVision* analysis. The Bureau of Land Management completed a study in 2018 exploring this concept in more detail.

Induced Seismicity

One notable challenge for the geothermal industry is the perceived risk of induced seismicity. Movement of fluids into or out of any well (e.g., water, oil and gas, geothermal) can induce or trigger some level of seismic or microseismic activity. The extent and magnitude of that activity and its proximity to property and people determines the level of potential risk. Injection of fluids under high pressures¹² and into critically stressed rock generally results in the greatest amount of seismic or microseismic activity.

High-pressure injection is uncommon in conventional geothermal energy extraction, and the risks to people and property are correspondingly small. However, higher-pressure stimulation technologies may ultimately

be required to achieve economic deployment of EGS, potentially elevating the risks of induced seismicity. The United States has demonstrated leadership in this area with a DOE-developed mitigation protocol to address induced seismicity from EGS.¹³ The geothermal industry will need to continue to proactively manage and reduce induced seismicity risks effectively and help the public discern between real and perceived risks. These goals can be achieved through ongoing communication with stakeholders (third objective) as well as through new and improved technologies that provide developers with greater understanding and control of potential induced seismicity. This topic is discussed in more detail in Doughty et al. 2018, and the *GeoVision* Roadmap includes potential actions to enhance understanding and management of induced seismicity in geothermal development.

Text Box 1-1. Technology Transfer between the Geothermal and Oil and Gas Industries Can Reduce Cost and Risk

The geothermal industry and the oil and gas industry use similar steps and technologies to locate and drill resources that are then used to produce energy. The resource characteristics, however, can differ substantially; for instance, oil and gas reservoirs tend to be under higher pressures than geothermal reservoirs, but at significantly cooler temperatures. Augustine 2016 provides an illustrative comparison of the differences in some key technical parameters between geothermal and oil and gas resources.

The geothermal industry is also smaller than the oil and gas industry in terms of both existing market value and number of industry participants. Despite these differences in resource environment and market size, the technology and intellectual capital transfer between the two can be bidirectional. Numerous advancements in geothermal technologies have been supported by adapting oil and gas technologies to conditions beyond their original technical limits. Likewise, the oil and gas industry has benefited from adapting technologies originally intended for use in geothermal energy.

The most notable example of geothermal technology transfer to the oil and gas industry is the research, development, and commercialization of polycrystalline diamond compact drill bits, led and supported by DOE for the geothermal industry. This innovation ultimately catalyzed the growth of a \$1.9 billion industry and resulted in cost savings for the oil and gas industry. As of 2006, polycrystalline diamond compact drill bits were used to drill roughly 60% of global footage (DOE GTO Multi-Year Research, Development, and Demonstration Plan 2008, Gallaher et al. 2010). By 2015, that number had increased to 90% of global footage (Scott and Hughes 2015). The use of these drill bits in offshore applications in the oil and gas industry has been estimated to reduce costs by \$58.54 per foot drilled, yielding cost savings of \$15.6 billion from 1982 to 2008 (DOE GTO Multi-Year Research, Development, and Demonstration Plan 2008, Gallaher et al. 2010).

¹² "High pressures" is defined as those approaching lithostatic pressures, which are confining pressures or the pressures exerted on a layer of rock by the weight of the overlying material.

¹³ DOE's Geothermal Technologies Office developed the "Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems" as a 7-step process for addressing induced seismicity concerns (Majer et al. 2012).



CHAPTER TWO

What is Geothermal Energy?

Erupting geysers surrounded by areas of geothermally altered ground.

Photo credit: Sigurdur William Brynjarsson

2 What is Geothermal Energy?

The term “geothermal” means “Earth heat” or “heat of the Earth.” Energy from geothermal resources has benefited humankind from its earliest origins. Prehistoric civilizations used hot springs and steam discharges (fumaroles) for cooking, heating, and therapeutic bathing; in modern terms, these uses are known as geothermal direct-use applications. In the United States, geothermal energy has provided affordable, reliable, and renewable energy since the 1890s, when the city of Boise, Idaho, began using geothermal resources for direct heating of commercial and residential buildings (Mink 2017). Since then, use of geothermal energy in the United States has expanded to include utility-scale electricity production, distributed heating and cooling applications, and the augmentation of various industrial processes.

Commercial geothermal electric power production began in the United States as early as September 1960, at The Geysers geothermal field in California. The Geysers remains the world’s largest geothermal field in terms of the number of operating power plants and wells, installed generation capacity, and the physical dimensions of the wellfield.¹⁴ As of 2017, the United

States was the global leader in both geothermal power generation and installed capacity (International Renewable Energy Agency 2017, Hanson and Richter 2017).

Geothermal heat pumps (GHPs) are another key geothermal technology considered in the *GeoVision* analysis. GHPs have been deployed since the 1940s, supplying reliable, quiet, efficient, and cost-competitive residential space heating and cooling (Battocletti and Glassley 2013).

2.1 Geothermal Resource Classes

Geothermal energy that is harnessed for both direct use and electricity generation comes from the heat that flows continuously from the Earth’s interior to the surface. This heat has been radiating from the Earth’s core for about 4.5 billion years. The temperature at the center of the Earth, about 6,500 kilometers (km) (4,000 miles) deep, is about the same as the surface of the sun (nearly 6,000°C, or about 10,800°F) (Figure 2-1).

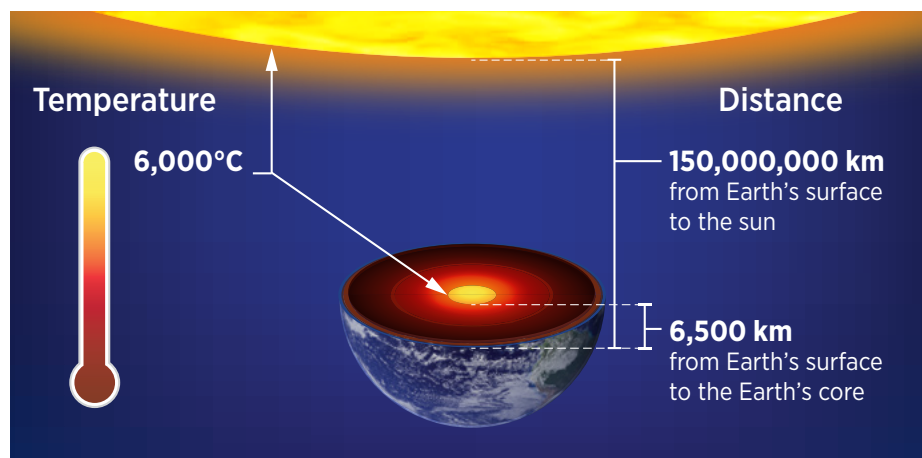


Figure 2-1. A conceptualized cut-away of the Earth, showing temperature increasing with depth to the Earth’s core, where the temperature is similar to the sun

¹⁴ Since 1960, more than 400 production wells and 28 power plants have been constructed across more than 45 square miles at The Geysers, producing a total peak installed capacity of 2,034 megawatts-electric (MW_e) (Calpine 2013, Calpine 2017). As of 2016, The Geysers geothermal field hosts 22 operating power plants with a total installed capacity of 1,821 MW_e that is supported by 350 operating wells (California Energy Commission 2018).

Geothermal energy is a renewable resource (Sanyal 2010, Lowry et al. 2017).¹⁵ The heat flowing from the Earth's interior is estimated to be equivalent to 44.2 terawatts-thermal (TW_{th}) of power (Pollack et al. 1993)—more than twice the amount needed to supply total global primary energy consumption in 2015 (Energy Information Administration [EIA] 2017a). This heat is continually replenished by the decay of naturally occurring radioactive elements in the Earth's interior and will remain available for billions of years, ensuring an essentially inexhaustible supply of energy (Blodgett and Slack 2009). Geothermal heat flow is expressed visibly at the surface as volcanoes, fumaroles, hot springs, and geysers. Although volcanoes represent the hottest and most visible form of geothermal energy, there is a range of such energy in the subsurface, with temperatures from thousands of degrees to a few degrees above ground-surface temperatures. Much of this energy can be used for productive purposes.

Temperatures above 150°C are widely—but not uniformly—distributed underground and become more common with increasing depth. Commercial electricity generation is generally economic from geothermal resources at temperatures above 150°C . Geothermal resource temperatures at a depth of 7 km (about 4 miles) are accessible with existing drilling technology (Figure 2-2).¹⁶ For comparison, the average depth of onshore oil and gas wells drilled in the United States in 2017 was about 3 km (just under 2 miles) (WorldOil 2017). The deepest borehole ever drilled—more than 12 km (about 7.5 miles)—was the Kola Superdeep Borehole, which was the result of scientific drilling activities in Russia (Ault 2015).

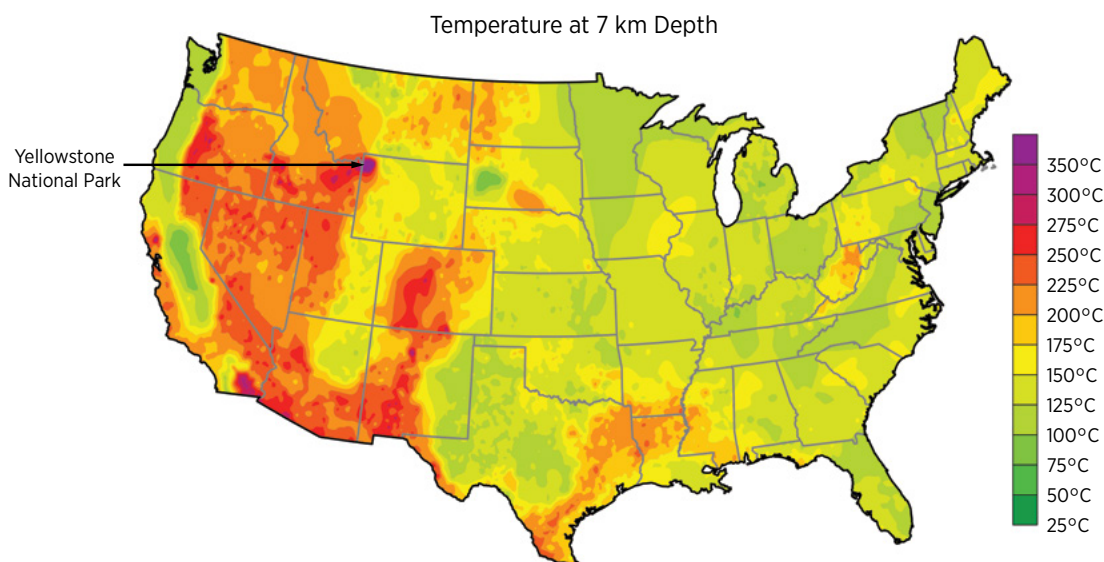


Figure 2-2. Temperatures throughout the contiguous United States at a depth of 7 km (about 4 miles)

Source: Blackwell et al. 2011

¹⁵ The Energy Independence and Security Act of 2007 (Pub. L. No. 110-140) defines geothermal energy as a renewable resource. Although distinct from wind and solar, which tap an instantly renewable energy source, geothermal is a renewable resource with lifecycles and timescales more similar to that of sustainable forestry.

¹⁶ Geothermal resource potentials for Alaska and Hawaii were not calculated in the *GeoVision* analysis and, as such, are not included in Figure 2-2. Text Box 2-1 provides more information.

Geothermal resources are unique compared to other renewable energy resources for several key reasons. First, some level of penetration of the Earth’s surface—usually drilling wells—is required to characterize, access, and efficiently extract geothermal resources. As such, geothermal energy has an inherent upfront resource cost and risk that other renewable resources do not have; determining where and how much the sun shines, wind blows, or rivers flow is generally easier, faster, and less costly. Data on renewable resources such as solar, wind, and hydropower are already collected by weather stations and satellites and are publicly accessible (e.g., National Renewable Energy Laboratory [NREL] Solar Data, NREL Wind Data).¹⁷

In addition, the way in which wind or solar energy is captured and converted for beneficial use is essentially the same regardless of resource quality. For instance, a location with a moderate amount of wind (e.g., Washington, D.C.) would use the same basic process to gather energy as would a windier location (e.g., Wichita, Kansas). In contrast, both the energy conversion process and end-use application of geothermal varies with resource quality, which is primarily a function of temperature. Once a geothermal power plant is built and operational, the energy produced is “always on.” Geothermal resources in a range of temperatures can be used economically for a variety of electric and non-electric applications. The *GeoVision* analysis considers the deployment and growth potential for a specific set of geothermal applications (Section 2.2).

In summary, geothermal energy resources and the means by which they are accessed and recovered vary greatly. The heat energy in geothermal resources exists in varying subsurface environments, and access can require differing techniques and technologies before the resource can be recovered for beneficial use. A single subsurface environment might also support more than one type of geothermal energy conversion. Figure 2-3 introduces the diversity of geothermal resources and some of their applications, as considered in the *GeoVision* analysis. These concepts are discussed in more detail in the subsequent sections.



A welder performing maintenance on production facilities at a geothermal power station. *Photo credit: Haim Shoshan*

¹⁷ Solar data are available on the NREL website at <https://www.nrel.gov/gis/data-solar.html>. Wind data are available on the NREL website at <https://www.nrel.gov/gis/data-wind.html>.

Geothermal Diversity

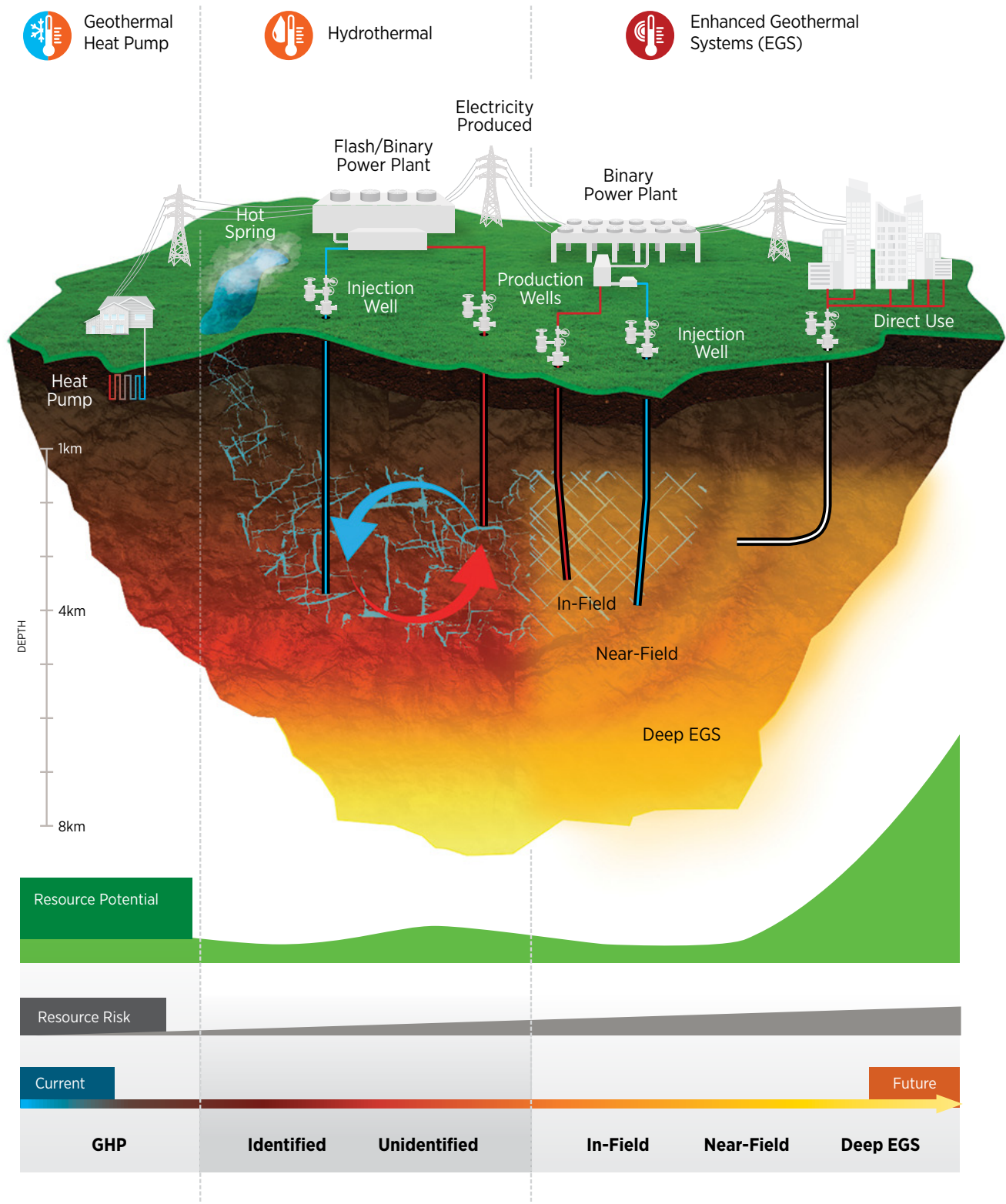


Figure 2-3. The diversity of geothermal resources and applications, delineated within three resource categories: geothermal heat pump, hydrothermal, and enhanced geothermal systems

The *GeoVision* analysis characterized three categories of geothermal resources:

Geothermal Heat-Pump Resources:

The ubiquitous presence of shallow soil, rock, and/or aquifers—and, specifically, their thermal storage properties—presents a vast and important geothermal resource. The thermal storage capacity of the shallow earth enables its use as a heat-exchange medium for low-grade thermal energy. GHPs use this thermal storage to increase the efficiency and reduce the energy consumption of heating and cooling applications for residential and commercial buildings. Shallow-earth resources exist across all 50 states and can be used for GHPs wherever the ground can be cost-effectively accessed to depths below seasonal temperature variations.¹⁸

Hydrothermal Resources:

Naturally occurring hydrothermal resources contain the basic elements of heat in the Earth, along with groundwater and rock characteristics (i.e., open fractures that allow fluid flow) sufficient for the recovery of heat energy, usually through produced hot water or steam. Hydrothermal resources can range in temperature from a few degrees above ambient conditions to temperatures greater than 375°C.¹⁹ Above this higher range, a new class of innovative subsurface and surface production technologies will likely be required to convert geothermal energy resources for beneficial use.

Enhanced Geothermal Systems:

Unconventional geothermal resources, often referred to as enhanced geothermal systems (EGS), contain heat similar to conventional hydrothermal resources but lack the necessary groundwater and/or rock characteristics to enable energy extraction without innovative subsurface engineering and transformation.

Unconventional EGS resources can be found at any above-ambient temperature that supports energy conversion for a given end-use technology application. The resource has potential applications across the geothermal technology spectrum, although practical application will be limited by the costs of required engineering.

The characteristics and geographic distribution of geothermal resources are summarized in the subsequent sections and discussed in greater detail in Renner 2006, Doughty et al. 2018, Augustine et al. 2019, Liu et al. 2019, and Young et al. 2019. In all cases, unless otherwise specified, the resource potential values indicated in this section represent technical potential in the United States—that is, the achievable energy generation given existing technology, system performance and environmental and land-use constraints (Lopez et al. 2012). These technical potential values were adopted as the resource potential starting points for the *GeoVision* analysis. Although Alaska and Hawaii offer immense geothermal potential (Text Box 2-1),²⁰ data limitations prevented those states from being modeled explicitly in the *GeoVision* analysis.



Sunrise glow on condenser steam at a geothermal power plant in Brawley, California. Photo credit: Piyush Bakane

¹⁸ On average, at soil depths greater than about 30 feet below the surface, ground temperatures are constant year round. Different system configurations enable GHPs to take advantage of thermal storage in the Earth at shallower or deeper levels in order to optimize the system costs and performance.

¹⁹ In thermodynamics, the “critical point” of a substance is the end point of a phase equilibrium curve separating a liquid and gaseous phase in terms defined by their pressure and temperature conditions. For pure water, the critical point occurs at 374°C and 220.64 bar (3,200 pounds per square inch absolute). Above the temperatures and pressures defined by the critical point, water exists as a supercritical fluid with unique properties characterized by high energy densities and low viscosities. Many natural systems contain water with salinities that move their critical points to temperatures of 400°C or beyond. Once supercritical geothermal conditions are encountered, innovative technologies will be required to develop those resources.

²⁰ The actual deployable resource potentials made available to the electric and non-electric sector modeling scenarios reflect adjustments to the resource supply curves to account for the removal of resources already developed and deployed; Alaska and Hawaii resource potentials, which could not be modeled in the *GeoVision* analysis (Text Box 2-1); and additional removal of resource potentials on federally protected lands. The methodologies and resulting supply curves used for the *GeoVision* modeling are detailed in Appendix C and Augustine et al. 2019.

Text Box 2-1. Geothermal Potential in Alaska and Hawaii

Alaska and Hawaii both have significant geothermal resources. The U.S. Geological Survey 2008 resource assessment indicates that Alaska has a mean conventional hydrothermal resource potential of 2,465 MW_e, representing about 6.3% of the total identified U.S. hydrothermal resource potential, and Hawaii has a mean conventional hydrothermal resource potential of 5,619 MW_e, representing about 14% of the total identified U.S. hydrothermal resource potential (Williams et al. 2008b). EGS resource potential is also likely to be substantial in these two states; however, the U.S. Geological Survey did not calculate this potential because information is insufficient to accurately estimate crustal temperatures on a regional basis.

Installed geothermal electricity generation capacity in Alaska and Hawaii includes 0.73 MW_e at Alaska's Chena Hot Springs Resort and 47 MW_e at Hawaii's Puna Geothermal Field. There is significant potential for increased capture of both undiscovered and identified hydrothermal resources (Section 2.1.1) and any EGS resources determined to exist. Hawaii has a state renewable portfolio standard mandating 100% renewable power by 2045. Alaska has a non-binding goal to generate 50% of its electricity from renewable sources by 2025 (Alaska Energy Authority 2016, EIA 2017b). Hydropower is Alaska's largest source of renewable electricity, and the state has demonstrated interest in increased renewable power. As of 2016, wind power supplied nearly 75% of Alaska's non-hydroelectric renewable electricity (EIA 2017c).

The modeling tools used for the *GeoVision* analysis (Chapter 3) were developed primarily to model grid congestion and transmission issues for high-penetration renewable energy scenarios in the contiguous United States. The electricity grids of Hawaii and Alaska are not connected to the mainland grid, so they were not included in model development. Although this exclusion means that geothermal resources in Alaska and Hawaii could not be quantified in the *GeoVision* analysis, it also reflects the more localized—and, in some cases, isolated—nature of the Alaska and Hawaii grids. For grid systems with such attributes, geothermal energy can provide significant value in the form of local grid reliability.

2.1.1 Hydrothermal Resources

Hydrothermal resources are considered conventional geothermal resources because they can be developed using existing technologies. The natural formation of a hydrothermal resource typically requires three principal elements: heat, water, and permeability.²¹ When water is heated in the Earth, hot water or steam can become trapped in porous and fractured rocks beneath a layer of relatively impermeable caprock, resulting in the formation of a hydrothermal reservoir (Figure 2-4).²²

Geothermal water or steam may emanate naturally from

the reservoir and manifest at the surface as hot springs or geysers; but most stays trapped underground in rock, under pressure and accessible only through drilling. Hydrothermal resources can provide economic and renewable energy when the three principal elements of heat, water, and permeability are present in sufficient amounts to support cost-competitive energy-extraction rates. Hydrothermal resources are found primarily in the western United States and in Alaska and Hawaii, where the Earth's tectonic activity has resulted in areas with naturally elevated heat flow (Figure 2-5).

²¹ For the purposes of this report, the term "water" in the context of geothermal energy is assumed to be liquid water unless steam (water vapor) or another phase is specified. Permeability is a characteristic of rocks that describes the degree to which they are porous and/or interconnected by cracks or "fractures" that allow the storage and passage of water and steam.

²² In most cases, as geothermal reservoirs naturally evolve and form, they generate their own low-permeability, clay-rich caprock through the alteration of the host rocks at high temperatures and in the presence of water.

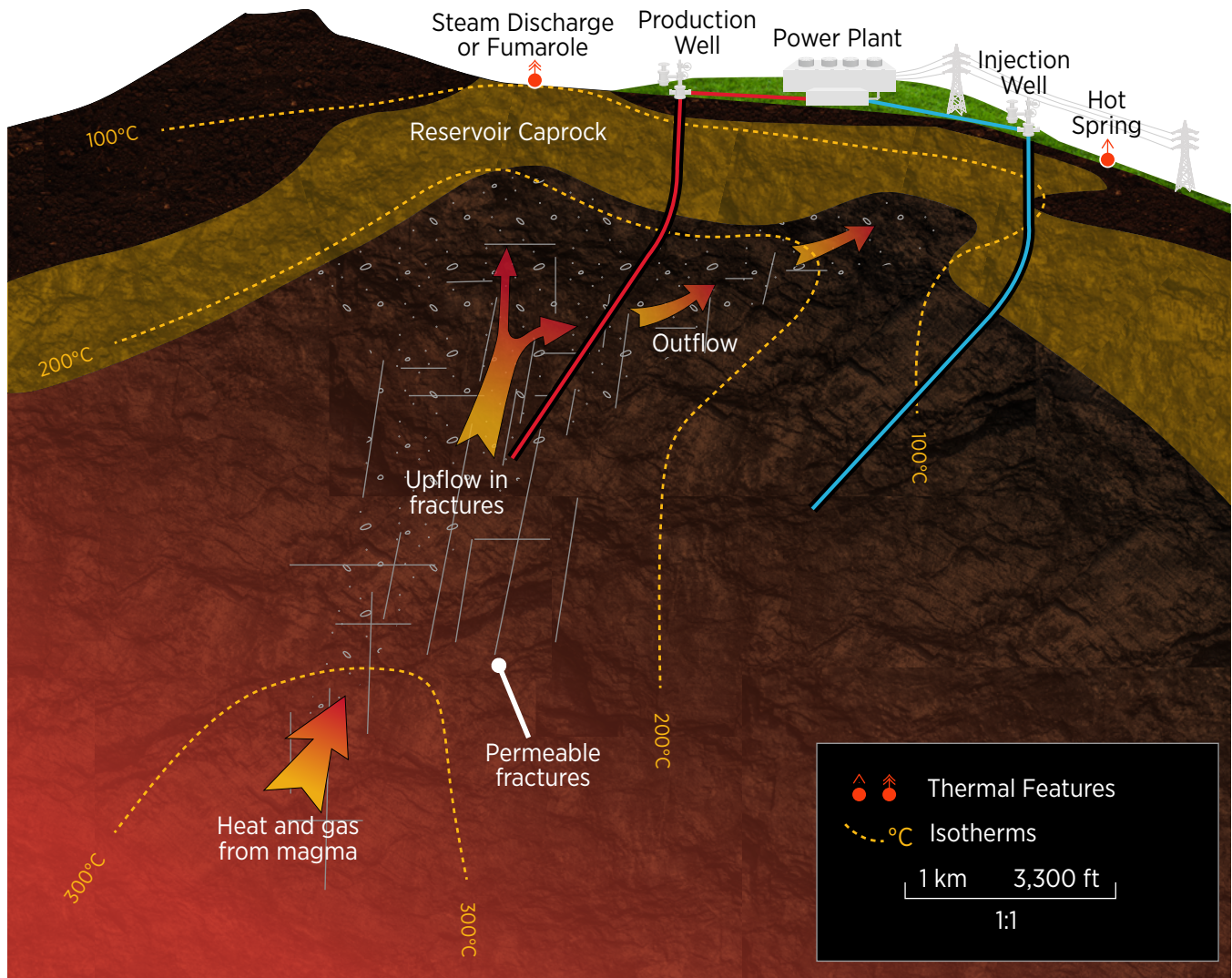


Figure 2-4. Idealized cross-section of a hydrothermal resource showing various conceptual elements of a high-temperature hydrothermal reservoir

Source: Modified and generalized after Cumming 2009

Figure Note: Figure indicates elements that are characteristic of naturally occurring, high-temperature hydrothermal systems in the range of about 250°C to >300°C, and those that are generally representative of most identified and developed hydrothermal systems. This figure illustrates an example in which hydrothermal fluids are heated by underlying magma which, along with gases, makes them buoyant and rise through fracture-hosted permeability in the system. A reservoir-confining structure, known as a caprock, defines the upper bounds to the hydrothermal reservoir. At shallower levels, hydrothermal fluids can often move laterally and—depending on the geology—may naturally emanate from the reservoir as thermal features (e.g., hot springs, geysers, fumaroles). Conceptualized temperature isotherms (lines of constant temperature) indicate the distribution of subsurface temperatures and an idealized production well (red) and injection well (blue) are drilled into the reservoir to, respectively, produce fluids for a power plant and recycle energy-depleted fluids through injection for sustainable, renewable power generation. Hydrothermal resources at temperatures below 250°C may also be found throughout the western United States and can exhibit different configurations, often characterized by deep circulation along structurally controlled and volumetrically more-restricted permeability. Magmatic influence may still play a role in these systems, although it is likely deeper than depicted in this figure; the main conceptual elements, however, are similar (Cumming 2009).

Conventional hydrothermal resources are sub-categorized by the U.S. Geological Survey as either “identified” or “undiscovered” (Williams et al. 2008a, Williams et al. 2008b). As the name implies, *identified* hydrothermal resources have already been identified or are otherwise known to exist through application of conventional exploration technologies and methods. Identified hydrothermal systems typically have at least some surface expression, such as a geyser, hot spring, fumarole, or other indication that a hydrothermal resource may exist at depth. Conversely, *undiscovered* hydrothermal resources are difficult to identify with existing exploration technologies and methods. This is true largely because these resources lack traditional surface manifestations that indicate subsurface resource potential. Existing geophysical techniques cannot reliably detect these systems or image them with a high degree of confidence. New exploration tools and technologies need to be developed to capture the resource potential of undiscovered, “hidden” resources. Initiatives supporting early-stage research and development efforts for such tools and technologies are detailed in Doughty et al. 2018. The application of new exploration tools and technologies in a robust, consistent, and systematic approach will improve the success rate of geothermal development projects while reducing overall exploration costs, thus improving access to financing for drilling.

The U.S. Geological Survey (USGS) resource assessment estimates that the *identified* hydrothermal resources of $>90^{\circ}\text{C}$ in the United States have the potential to provide a mean total of 9,057 megawatts-electric (MW_e) of electric power generation (Williams et al. 2008a, Williams et al. 2008b). The USGS estimated hydrothermal resource potential through a combination of two methods: 1) volumetric methodologies, where recoverable heat is estimated from the thermal energy available in a reservoir of uniformly porous and permeable rock for an assumed producible fraction of a reservoir’s thermal energy, and 2) resource temperature estimates interpolated from available exploration and production well data, or the use of chemical geothermometers applied as temperature proxies where *in-situ* temperature measurements were unavailable. The complete methodology is in Williams et al. 2008a. The assessment includes resources $>90^{\circ}\text{C}$ in its estimate of power potential.

USGS predicts another 30,033 MW_e of *undiscovered* hydrothermal resource potential remaining undeveloped (Williams et al. 2008a, Williams et al. 2008b). USGS

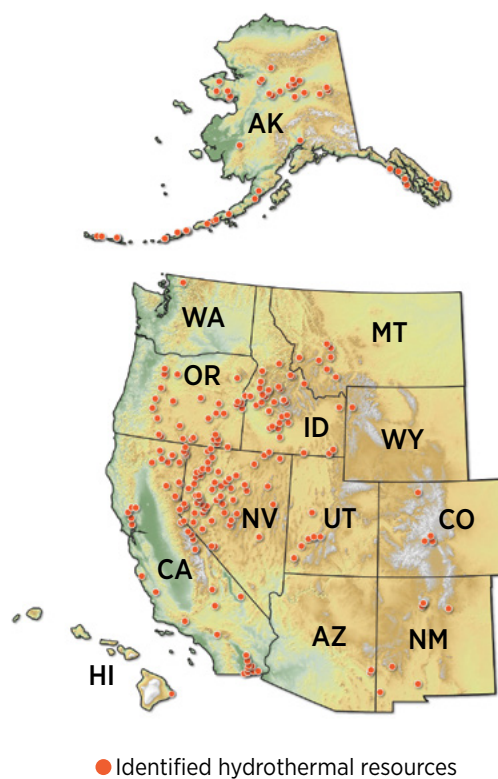


Figure 2-5. Map illustrating the location of identified hydrothermal resources in the United States (represented by the red dots) included in the 2008 U.S. Geological Survey geothermal resource assessment

Source: Williams et al. 2008b

estimated the undiscovered hydrothermal resource using geographic information system-based statistical methods to analyze the correlation between spatial data sets and existing geothermal resources. This correlation was used to derive the probability of the existence of geothermal resources in unexplored regions. Due to the probabilistic nature of the USGS assessment, the undiscovered geothermal resource power generation potential has a 95% probability of being at least 7,917 MW_e and a 5% probability of being up to 73,286 MW_e . For the *GeoVision* analysis, the mean value of 30,033 MW_e was used; of this, 25,810 MW_e occurs in the contiguous United States. The actual characteristics of these undiscovered hydrothermal resources, such as reservoir depth and temperature, are largely unknown. For the purpose of estimating resource development costs in the *GeoVision* analysis, it was assumed that the undiscovered resources would be similar in nature to identified hydrothermal sites in a given region, and undiscovered resource characteristics were based on the mean capacity-weighted average value of resource

parameters from identified hydrothermal sites in the same region (Augustine et al. 2019).

At temperatures below the range traditionally used for electric power generation ($<150^{\circ}\text{C}$),²³ the total U.S. low-grade conventional geothermal resource capable of supporting geothermal direct-use (non-electric sector) applications is about 3.6 million gigawatt-hours-thermal (GWh_{th})—that is, 12 quadrillion British thermal units, or 12 quads. Expressed as a capacity value, this equates to 13.7 gigawatts-thermal (GW_{th}).²⁴ If sedimentary resources are included—including those traditionally used for oil and gas production that also exhibit elevated temperatures²⁵—the total resource increases to 11.2 million GWh_{th} (38 quads, or 43 GW_{th}) (Mullane et al. 2016).²⁶ By comparison, the entire U.S. residential sector used about 4.5 quads of natural gas for heating, cooking, and clothes drying in 2016 (EIA 2017d).

2.1.2 Unconventional Resources (Enhanced Geothermal Systems)

The principal elements of heat, water, and permeability—when found together and in sufficient amounts—can support cost-competitive rates of energy extraction. Independent of water and permeability, thermal energy (heat) exists everywhere on Earth and increases with depth. Research funded in part by the U.S. Department of Energy (DOE) in the 1970s opened new frontiers of geothermal resources by studying EGS.²⁷ At the most basic level, EGS are manmade geothermal reservoirs. Where the subsurface is hot but contains little permeability and/or fluid, pumping water into wells could stimulate the formation of a geothermal

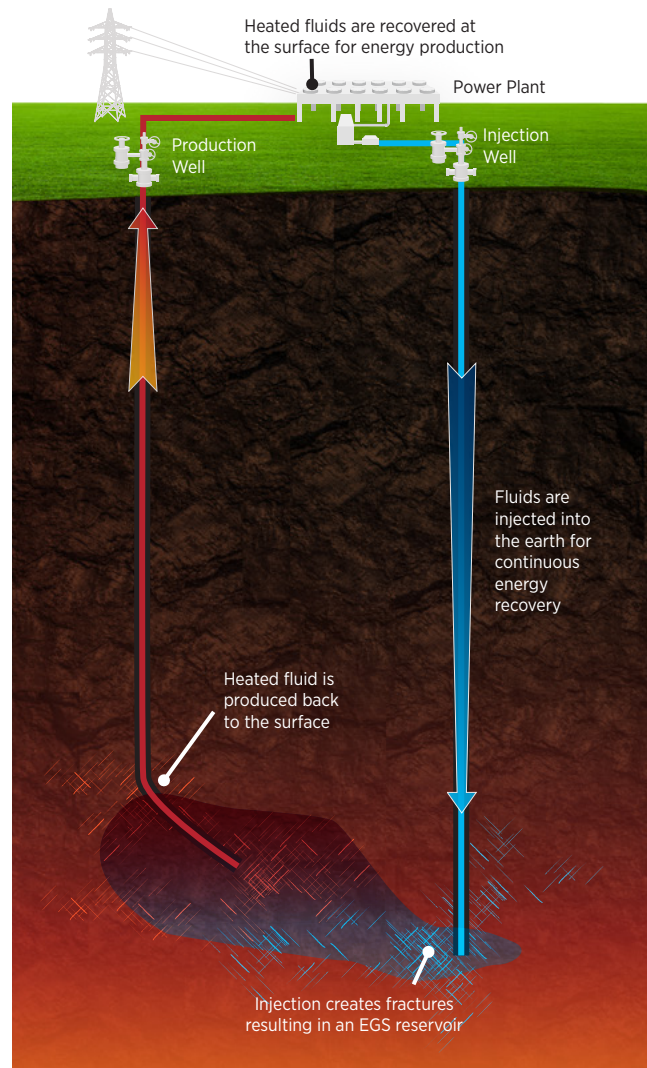


Figure 2-6. Conceptualization of an enhanced geothermal system

²³ The actual temperature below which electricity generation is no longer commercially feasible depends on the specific resource, its physical characteristics and thermodynamic state, the cost to access it, its location, and the cost of alternative electricity sources, among other things. Commercial electricity generation is generally economic from geothermal resources at temperatures above 150°C . However, there are several examples of commercial geothermal projects producing electricity from reservoir temperatures well below 150°C . Some examples of these projects include Chena Hot Springs (Alaska), Amedee (California), Raft River (Idaho), Neal Hot Springs (Oregon), and Wabuska (Nevada).

²⁴ Conversion of geothermal heat energy resource to capacity was done following the conventions established in U.S. Geological Survey Circular 892, assuming a 30-year system life with a 100% capacity factor (USGS 1983).

²⁵ Geothermal energy generation from reservoirs and basins with elevated temperatures that have traditionally been used for oil and gas production has been demonstrated multiple times and is an area of active research (e.g., Pleasant Bayou [Texas], Rocky Mountain Oil Testing Center [Wyoming], and Denbury [Mississippi]) (see Campbell and Hattar 1990, Reinhardt et al. 2011, Clark 2012, DOE 2016b).

²⁶ Sedimentary geothermal basins are defined as, “thermal sedimentary aquifers overlain by low thermal-conductivity lithologies [that] contain trapped thermal fluid and have flow rates sufficient for production without stimulation” (Mullane et al. 2016). These sedimentary geothermal resources were explicitly captured in Mullane et al. 2016 for direct-use applications and were therefore considered in the *GeoVision* analysis of direct-use district heating. For the purposes of the *GeoVision* analysis, sedimentary resources could not be explicitly considered as part of the resource supply curves for modeling electric-sector deployment.

²⁷ The U.S. Atomic Energy Commission initially sponsored research on hot, dry-rock EGS, followed by the U.S. Energy Research and Development Administration, and, eventually, DOE. The Federal Republic of Germany and Japan contributed significant funding and technical staff through an International Energy Agency agreement (DOE 2010).

reservoir capable of supporting commercial rates of energy extraction (Figure 2-6). Although the DOE has focused on using EGS to achieve commercial electricity generation, the *GeoVision* analysis demonstrates that EGS can also support growth of geothermal direct-use applications such as geothermal district heating.

EGS offer the opportunity to access enormous amounts of thermal energy in the Earth by drilling wells and connecting them with an engineered fracture network. Water can then be circulated to harness energy in the form of heat and convert it to electricity, district-level heating solutions, or other geothermal direct-use applications. Creating a manmade reservoir that minimizes subsurface water losses and that can sustain economic heat recovery presents challenges that will require innovative new technologies. The U.S. geothermal industry has conducted considerable research in these areas. Realizing the full potential of EGS resources will require continued early-stage research in faster, lower-cost drilling tools and methodologies; reservoir stimulation technologies to create manmade geothermal reservoirs; and new reservoir modeling tools and management approaches to ensure the sustainability of these engineered systems. These technologies will be essential to improving well productivity and lowering development costs. This could ultimately make EGS economically viable and allow the United States to capture the many potential benefits offered by EGS resources.

With technology improvements, EGS could be engineered cost effectively wherever there is hot rock at accessible depths, enabling economic capture of EGS potential nationwide. The total EGS resource potential used in the *GeoVision* analysis was based on an assumed depth cut-off of 7 km and minimum temperature of 150°C (Figure 2-2) and estimated on that basis to be at least 5,157 gigawatts-electric (GW_e)²⁸ (Augustine 2016, Augustine et al. 2019) for power-generation purposes—nearly five times the total installed utility-scale electricity generation capacity in the United States in 2016 (1,074 GW_e) (EIA 2017e). As innovative drilling and stimulation technologies enable

access to greater depths and reduce drilling and engineering costs, larger volumes of high-temperature EGS resources than those considered in the *GeoVision* analysis could be harnessed (Augustine 2011).

Economic EGS reservoirs could also support vast geothermal direct-use market potential. Data from Mullane et al. 2016 and Beckers and Young 2017 estimate an EGS-based resource of roughly 15 million terawatt-hours-thermal (TWh_{th}) available to homes and businesses through geothermal district heating—a key direct-use technology application and focus area for the

Technologies that support longer-term economic EGS resource capture can provide significant near-term value. Results are likely to include the economic and reliable conversion of subcommercial conventional wells to useful injection or production wells. This can benefit existing geothermal installations and future development of conventional hydrothermal resources by decreasing the costs and risks associated with drilling and developing conventional hydrothermal wells.

GeoVision analysis. Compared to a total U.S. annual energy consumption of 1,754 TWh_{th}²⁹ for residential and commercial space heating, this EGS-based resource is theoretically sufficient to heat every U.S. home and commercial building for at least 8,500 years (EIA 2009, EIA 2012). Practical potential, however, is constrained by technical and economic factors. Research and development progress has been made for EGS, but the technology is still in the early stages of implementation and full commercialization is likely to be more than a decade away (Ziagos et al. 2013). The *GeoVision* analysis accounts for practical limitations in its estimates of EGS potential for both the electric and non-electric sectors.

²⁸ Gigawatts-electric is power available in the form of electricity generated from the conversion of heat or other potential energy.

²⁹ The 1,754 TWh_{th} annual energy consumption was estimated as the summation of the most recent data available from the EIA's 2009 Residential Energy Consumption Survey and 2012 Commercial Buildings Energy Consumption Survey.

2.1.2.1 In-Field, Near-Field, and Deep Enhanced Geothermal Systems

EGS include a spectrum of resources—from low-permeability resources within existing conventional hydrothermal locations, called “in-field” resources, to previously unexplored and undeveloped “deep” resources (Figure 2-3). Developing EGS and deploying EGS-enabling technologies is expected to happen in stages along this resource spectrum. The *GeoVision* analysis assumes the progression described in this section: from in-field to near-field to deep-EGS deployment.

Initial EGS resource development and EGS technology deployment will likely occur with in-field resources, at the sites of existing conventional hydrothermal projects. In conventional hydrothermal development, resource uncertainties occasionally result in the completion of non-productive wells. In-field EGS resource development would apply EGS technologies to these sub-commercial wells, enabling their conversion from stranded to producing assets. EGS technologies could engineer connections from initially sub-economic wells to a productive, conventional reservoir, making heat recovery from additional volumes of hot rock both

possible and cost effective. In this way, application of EGS technologies could capture additional resource volumes not part of the initial development, as well as decrease the costs and risks associated with drilling and developing conventional hydrothermal wells.

The existing geothermal industry has implemented the in-field EGS approach with varying degrees of success. The most promising results thus far have emerged from innovative well stimulation combined with other improved EGS technologies. These results indicate an opportunity to continue to improve EGS technology, increase rates of success, and capture additional in-field EGS resources. Examples of this are detailed in Doughty et al. 2018 and include DOE-funded EGS demonstration projects at the Northwest Geysers (California) (Garcia et al. 2016), Desert Peak (Nevada) (Chabora et al. 2012), Brady’s Hot Springs (Nevada) (Drakos and Akerley 2015), and Raft River (Idaho) (Bradford et al. 2015, Bradford et al. 2016), as well as commercial success at Soda Lake (California) (Lovekin et al. 2017).

Once improved technologies enable the industry to consistently and reliably capture in-field EGS resources, the next likely stage for EGS development would be in the near-field environment, or the zones of hot rock extending beyond the margins of conventional geothermal resources. The areas around existing hydrothermal systems are typically hot as a result of the nearby thermal anomaly and are relatively well characterized, but lack permeability and a connected fracture network. Applying improved technology to near-field EGS resources expands the ability to harness additional resources beyond the in-field environment. In-field and near-field EGS present the most readily available opportunities for EGS developments because the majority of the critical power-generating infrastructure is already in place and operational. The progression from reliable capture of in-field EGS resources to repeatable success in near-field EGS environments is likely to produce a major step-change in EGS development rates.

As EGS subsurface engineering techniques are refined, the expectation is that they will be applied to the final stage of EGS development: at least 5,157 GW_e of stand-alone, deep-EGS resources (Augustine et al. 2019). The *GeoVision* analysis envisages that developers can



Geothermal steam turbine blades. Photo credit: Betsy Phillips

use innovative technologies to access volumes of rock with high temperatures but with initial permeabilities that are insufficient to support commercial flow rates and/or that lack reservoir water. Deep-EGS reservoirs would then be formed by drilling wells into this rock and creating a commercial fracture network via well stimulation. This network would enable harvesting of thermal energy by producing hot fluids for electricity generation or other geothermal direct-use applications such as geothermal district heating.

2.1.3 Geothermal Heat Pumps

GHP resources refer to the shallow-earth environment composed of rocks and soils at depths from a few feet below ground to average depths of about 30 feet. At these depths, ground temperatures are constant year-round and the thermal energy storage properties of the rocks and soils allow them to act as a heat *sink*—absorbing excess heat during summer, when surface temperatures are relatively higher—and as a heat *source* during the winter, when surface temperatures are lower. GHPs take advantage of the

ground’s thermal-storage properties, using thermal energy removed from buildings and seasonally stored in the ground during summer cooling operations to keep buildings warm in the winter at reduced rates of electricity consumption. In addition, GHPs cool buildings at higher efficiencies than conventional air conditioners because the temperature of the shallow earth is cooler than ambient air in summer (Liu et al. 2019). The nation’s GHP resource is extensive enough to theoretically support any level of GHP deployment; as such, the total resource potential was not calculated in the *GeoVision* analysis. The *GeoVision* analysis did, however, assess GHP resource technical potential—a subset of total resource potential that accounts for technical and economic constraints.³⁰ Results indicate that more than 580,000 GW_{th}³¹ of GHP resource technical potential are available nationwide.

2.2 Geothermal Energy Production

The geothermal resources described in Section 2.1 support a range of applications for electric and non-electric energy production (Figure 2-7). Some applications use the Earth’s temperatures near the surface, whereas others require drilling miles underground. The specific use for a geothermal resource depends on the resource temperature. Geothermal resources with the highest temperatures (150°C or greater) are generally used to produce electricity. Lower-temperature resources can support geothermal direct-use applications in commercial and residential buildings, industrial processes, agricultural applications, and recreation. In the shallow-earth environment, where ground temperatures are relatively constant, GHPs can provide efficient residential and commercial heating and cooling. Geothermal energy also offers a number of beneficial characteristics, including the ability to provide reliability services to the grid. These attributes are discussed in Section 2.3.



Galena II geothermal power station with the Sierra Nevada mountains in the background. Photo credit: Gad Shoshan

³⁰ Technical potential is defined as the amount of technically feasible, developable GHP capacity after considering siting constraints and system performance.

³¹ GHP potential is reported as gigawatts-thermal, or GW_{th}. Unlike geothermal electricity generation reported in gigawatts-electric, or GW_e, or geothermal direct use reported in gigawatt-hours thermal, or GW_{th}, GHPs do not rely on thermal energy from the Earth as the energy source for operation. Instead, GHPs use electricity to power a heat pump and use the ground as a heat sink in summer for cooling (rejecting heat to the ground) and as a heat source in winter for heating (extracting heat from the ground). Depending on location and operation, the annual transfer of thermal energy from a GHP to the ground can be net positive, net negative, or neutral (if year-round heat-extraction and heat-rejection loads are perfectly balanced). In this report, GHP potential is described only in terms of the heating and cooling capacity (in GW_{th}) that it enables.

Power Generation

Direct Use

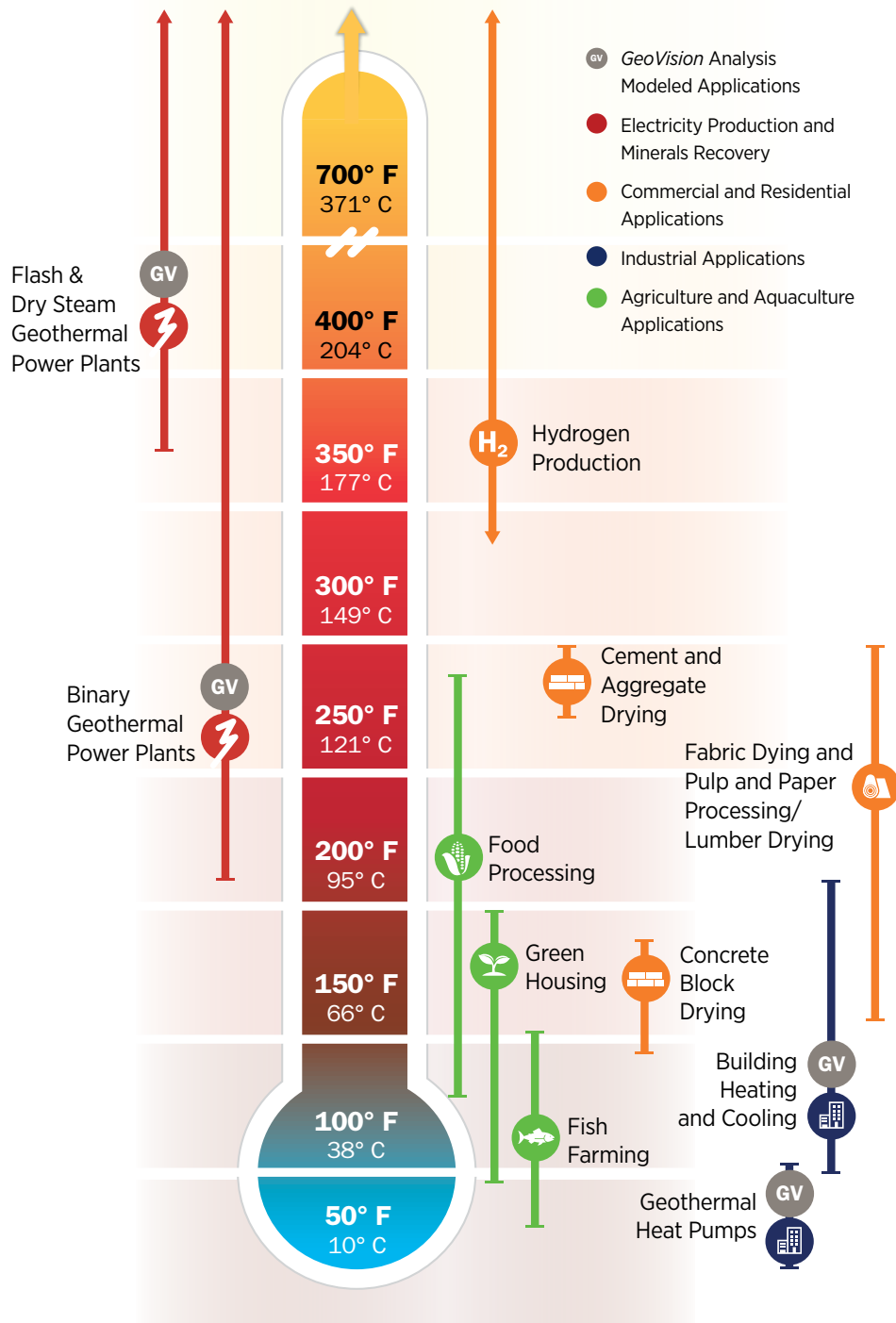


Figure 2-7. The continuum of geothermal energy technology applications and uses

Figure Note: As noted previously, geothermal power production can occur at resource temperatures below 150°C, but such projects tend to be the exception and require a combination of technical, economic, and access factors that enable development.

The *GeoVision* analysis considered capacity deployment and expansion by modeling three primary technology applications of geothermal energy resources: (1) electricity generation from geothermal power plants, supported by either hydrothermal or EGS resources; (2) geothermal district heating, a geothermal direct-use application, supported by either hydrothermal or EGS resources; and (3) GHPs, supported by GHP resources in the shallow-earth environment. Sections 2.2.1–2.2.4 elaborate on these technology applications.

2.2.1 Electric Power Generation

One of the key uses of geothermal energy is electric-power generation using three basic types of geothermal power plants: dry steam, flash steam, and binary (Figure 2-8). Each power-plant configuration features different energy-conversion efficiencies and different operating requirements that influence sustainable management approaches for the associated geothermal resources. Operational characteristics influence reservoir performance, thus requiring proactive management of both the plant and reservoir (Text Box 2-2). Variety in power-plant designs affords developers the opportunity to optimize the geothermal resource of interest and meet the needs of the application and end users. Differences in efficiencies and operating requirements ultimately impact power-plant capital costs, with dry-steam and flash-steam power plants generally being the least expensive on a $\$/kW_e$ basis relative to binary power plants.³²

Geothermal power-plant developments generate electricity from steam or hot water supplied by production wells drilled into the resource. The hot water or steam powers a turbine that turns a generator to produce electricity. The energy-depleted fluids are recirculated back into the Earth where they recover additional heat to support constant, renewable geothermal energy extraction. Existing geothermal power-plant technologies use conventional hydrothermal resources. Improved resource engineering technologies could facilitate the use of EGS resources for electricity generation, with minimal or no modification required to existing power-plant technologies.

Text Box 2-2. Best-Practice Management—Geothermal Electric Sector

Proactive management of a geothermal field and power plant begins with a comprehensive monitoring and data-collection program that includes pressure, temperature, chemistry, and geophysical surveys on the reservoir, wells, pipelines, and power-plant infrastructure. Best-practice management leverages the value of these data by engaging a technical resource team staffed with engineers and geoscientists. The team integrates the data into a calibrated, full-field resource and asset model that can forecast performance in response to existing operational conditions and proposed operational changes. This comprehensive approach provides the most effective decision-management tool available to geothermal developers and operators. New technologies, such as applications of machine learning, could further enhance geothermal best-practice management.



A field engineer setting up well flow test equipment at the Hudson Ranch geothermal power plant in California.

Photo credit: Don B. Dale

³² Overnight capital costs for an example flash power plant are $\$4,683/kW_e$ versus $\$5,603/kW_e$ for binary power-plant technologies (Cole et al. 2017). Overnight capital costs are defined as the capital expenditure required to achieve commercial operation of a plant, excluding the construction period and the financing and interconnection costs.

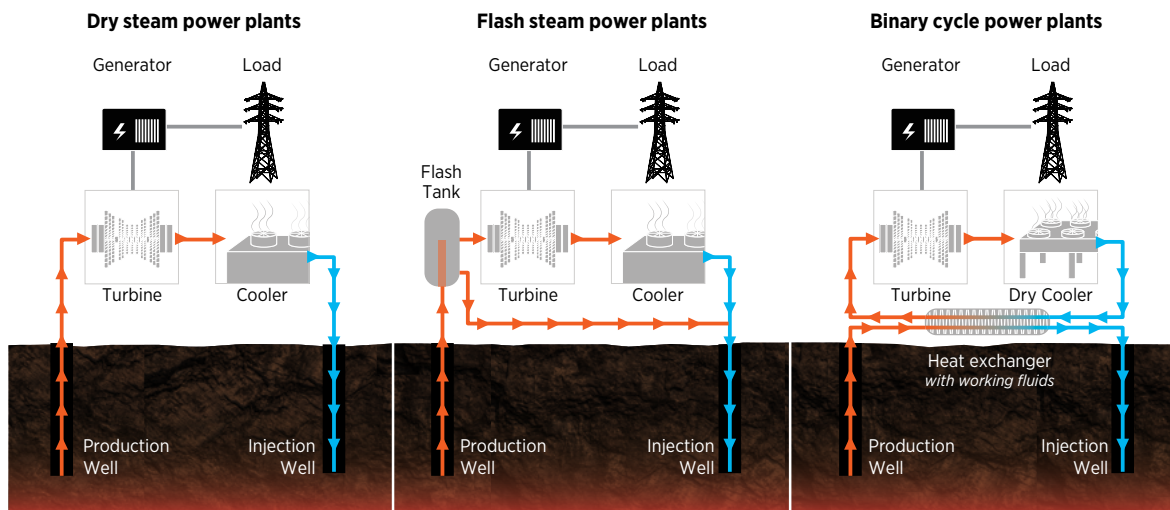


Figure 2-8. Geothermal power-plant configurations: dry steam, flash steam, and binary cycle

As of 2017, the United States led the world in the amount of electricity generated from geothermal resources (International Renewable Energy Agency 2017, Hanson and Richter 2017). As of 2016, 3,812 MW_e of installed geothermal capacity provided an average of 2,542 MW_e of net summer capacity^{33, 34} to the U.S. grid, generated nearly 15,920 gigawatt-hours-electric (GWh_e) of electricity annually, and supported a workforce of 7,645 employees (DOE 2017, Augustine et al. 2019) (Figure 2-9). Geothermal net summer capacity has been growing at a rate of about 2% per year and is projected to exceed 2,900 MW_e by 2022 (Augustine et al. 2019).

As of 2018, geothermal power plants were concentrated in the western United States (Figure 2-10), with the majority located in California and Nevada. Although geothermal energy accounts for only 0.4% of total electricity generation nationwide, it provides 6% of total generation in California and 8% in Nevada (EIA 2016). The state of California alone has more installed geothermal capacity than any country in the world (Bertani 2015, International Renewable Energy Agency 2017).

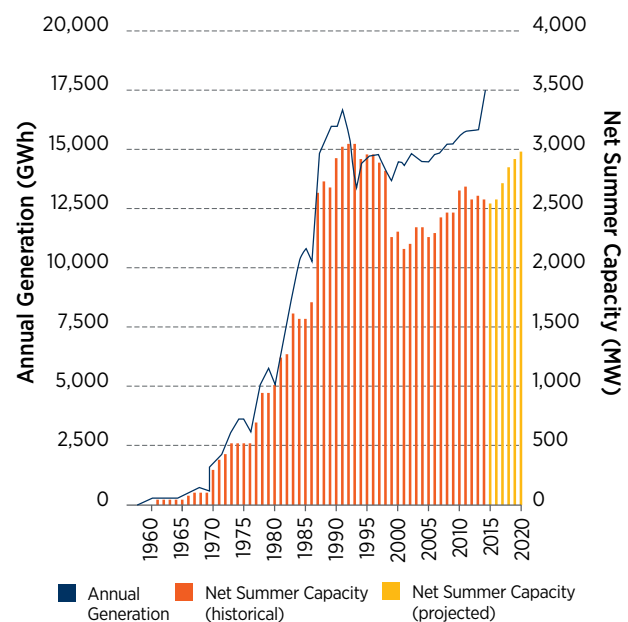


Figure 2-9. U.S. historical annual geothermal electricity generation (in GWh_e) and installed net summer capacity (in MW_e)

Source: Augustine et al. 2019

Figure Note: The drop in net summer capacity from 2000 to 2001 reflects a combination of retirements and derating of some power plants at The Geysers geothermal field.

³³ Net summer capacity is defined by EIA as, “The maximum output, commonly expressed in MW, that generating equipment can supply to system load, as demonstrated by a multi-hour test, at the time of summer peak demand (period of June 1 through September 30).”

³⁴ Installed (nameplate) and net capacities differ largely because of power-plant derating at The Geysers geothermal field. At Geysers, the reservoir is not able to supply all the production necessary due to productivity decline or insufficient make-up well drilling. This attribute accounts for roughly 800 MW_e of the differential, and improved technologies for both conventional (hydrothermal) and unconventional (EGS) resources will be essential to overcoming these types of limitations. The remaining differential occurs because geothermal power plants provide their own power for plant operations, which includes power to operate pumps that produce and inject geothermal brines underground. Additionally, the net summer capacity is below the optimal net capacity because plants that use air cooling do not operate as efficiently at high ambient temperatures.

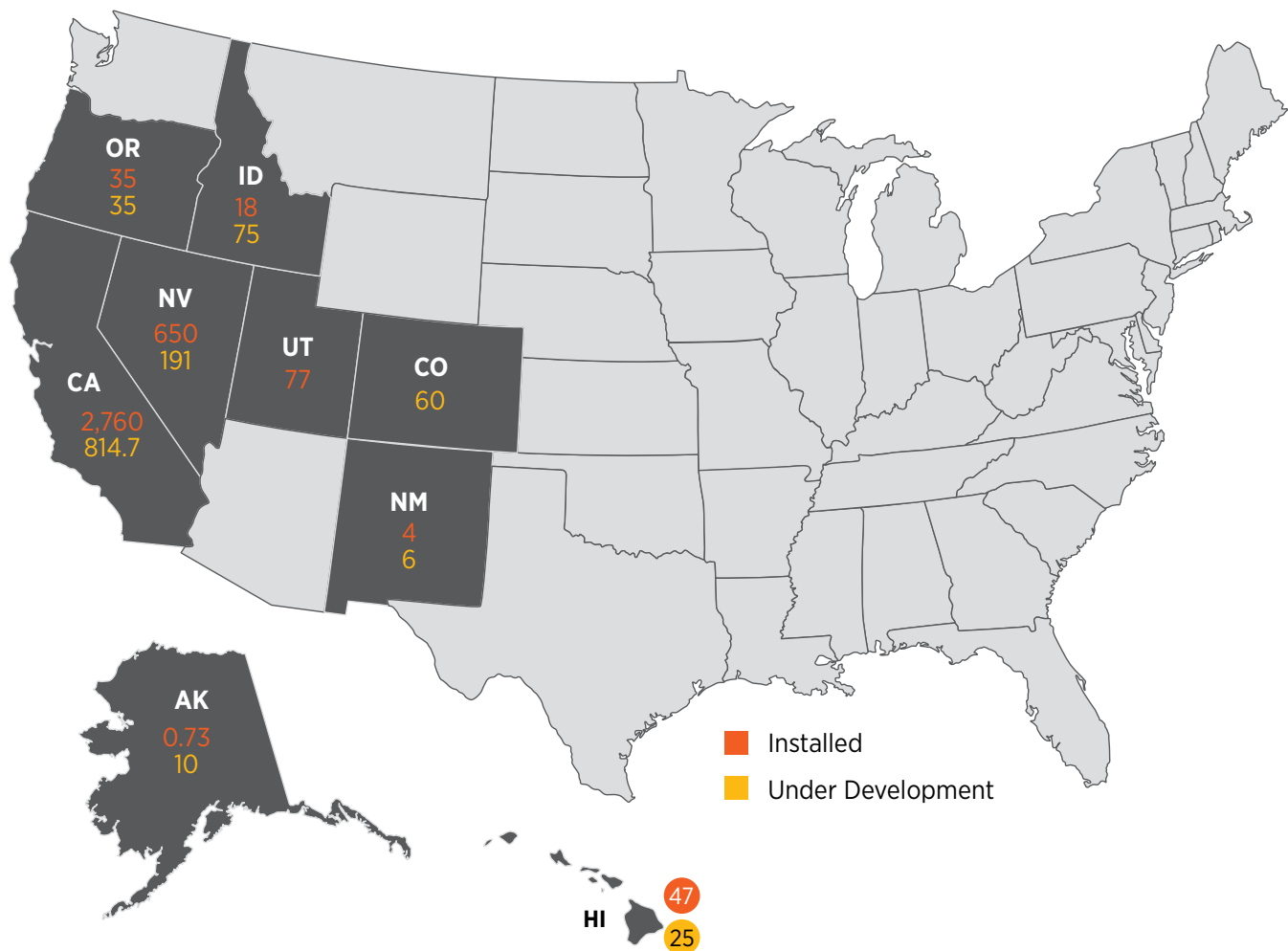


Figure 2-10. Existing and planned U.S. geothermal installed capacity (MW_e) by state

Source: Roberts 2018 (using Geothermal Energy Association data, as cited in Roberts 2018)

2.2.2 Geothermal Direct Use

The *GeoVision* analysis quantified and evaluated geothermal district-heating applications of geothermal direct-use resources. These applications use hot water from geothermal resources with temperatures below about 150°C, where electric-power generation has not historically been cost effective (McCabe et al. 2019). In geothermal district-heating applications, water from the geothermal resource is piped through heat exchangers or directly into commercial or residential buildings to meet heating and hot-water demands for entire districts.

In the United States, the most well-known and longest-running geothermal district-heating system is

located in the city of Boise, Idaho. The system has been operating since the 1890s and features the addition in 2012 of 60,000 m² of floor area from Boise State University to the city's geothermal district-heating system (Lund and Boyd 2015, Mink 2017). As of 2016, the United States had only 21 installed and operating geothermal district-heating systems, representing a total installed capacity of about 100 MW_{th} (Snyder et al. 2017). For comparison, 257 geothermal district-heating systems were in operation in Europe as of 2015, with a total installed capacity of 4,702 MW_{th} (Angelino et al. 2016)—49% of total global installed direct-use capacity (9,600 MW_{th}) (Antics et al. 2016). More information about the types and installed capacities of direct-use installations in the United States can be found in Snyder et al. 2017.

As illustrated in Figure 2-7, direct-use geothermal applications extend beyond geothermal district heating. Other uses include greenhouses and aquaculture (e.g., fish farming), food processing (e.g., agricultural drying and beer brewing), and industrial uses where process heat is required (e.g., pulp and paper processing, and drying of cement, aggregate, lumber, and other materials). Such applications are anticipated to hold significant potential for deployment growth in geothermal direct-use applications and the conventional hydrothermal and unconventional EGS geothermal resources that support them. Determining the market-deployment potential and impacts of these additional geothermal direct-use applications was outside of the scope of the *GeoVision* analysis and they are not quantified in this report.

2.2.3 Geothermal Heat Pumps

U.S. residential and commercial heating and cooling demand can be met using geothermal heat pumps, typically noted as GHPs and sometimes called “ground-source heat pumps.” GHPs use the thermal storage properties of the shallow earth to provide efficient heating and cooling. Temperatures at an average depth of 30 feet remain relatively constant—between about 10°C (50°F) and 15°C (59°F). For most areas, this means that soil temperatures are usually warmer than the air in winter and cooler than the air in summer. As described in Section 2.1.3, GHP technologies make use of this consistent temperature to hold excess heat and then release it as needed. GHP systems can be used almost anywhere to heat and cool homes and buildings as well as to supply hot water.

A GHP system includes 1) a ground heat exchanger, which is a group of pipes buried in the ground, immersed in a surface water body, or exchanging heat directly with groundwater; 2) an energy-delivery system such as a heating, ventilation, and air-conditioning (HVAC) system with ductwork for forced-air heating/cooling, and/or in-floor piping for radiant heating; and 3) a heat pump, which pumps thermal energy between the delivery system and the ground heat exchanger. The ground heat exchanger transfers heat between the ground and a fluid, usually a water/antifreeze mixture. There are several types and configurations of ground heat exchangers (Figure 2-11). The majority (84%) of GHP systems in the United States use closed-loop

ground heat exchangers; slightly more than half are in a vertical closed-loop configuration, and slightly less than half are in a horizontal closed-loop configuration. The remaining 16% of GHP systems use groundwater or surface water in an open- or closed-loop configuration (Lund 2001, Liu et al. 2019). Figure 2-11 illustrates closed- and open-loop systems using groundwater or surface water.

The variety of loop configurations enables GHP systems to achieve efficiency and system performance while accommodating physical constraints imposed by site dimensions or infrastructure access. For example, in areas with few land-access constraints, horizontal loops at shallow depths of just a few feet can support efficient, low-cost GHP systems. In densely populated urban areas, where land access might be limited, vertical-loop configurations in wells drilled from tens of feet up to a few hundred feet can achieve similar results.



Klamath Basin Brewing Company's Creamery Brewpub in Oregon. The brewery uses geothermal fluids from the city's district-heating system to brew its beer. Photo credit: Ryan Cole and Paul Schwering

Once installed, the ground heat exchanger is connected to a geothermal heat pump, which pumps the thermal energy from the ground into the indoor energy-delivery system in the winter months. During summer months, the system can operate in reverse, becoming an air conditioner and using the ground heat exchanger to disperse excess heat from indoors to the ground, where it is stored for use the subsequent winter.

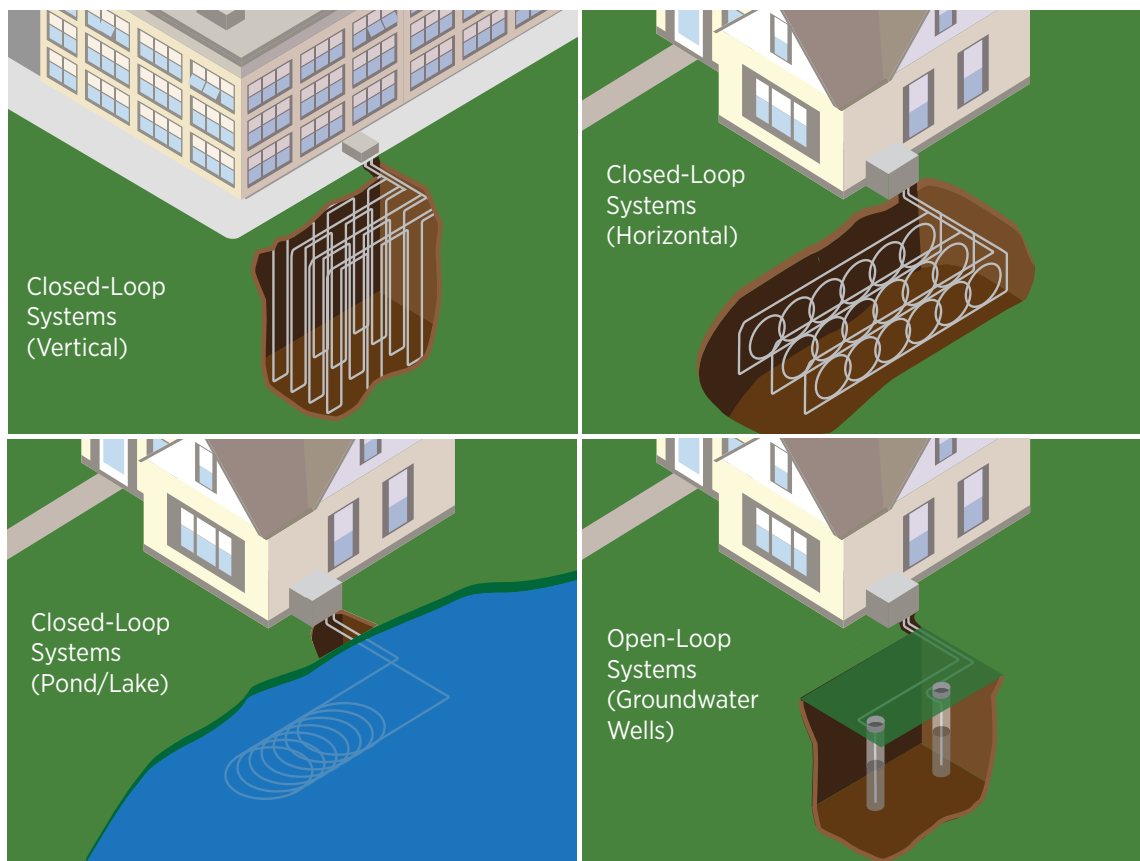


Figure 2-11. Illustrations of commonly used closed-loop and open-loop ground heat exchangers

Figure Note: The distribution of ground heat exchanger types used in GHP systems in the United States is vertical closed loop (upper left) 46%, horizontal closed loop (upper right) 38%, surface-water closed loop (bottom left) 10%, and groundwater open loop (bottom right) 6%. For illustrative purposes only. See page 39 for example photo.

Figure 2-12 illustrates the simplified process for an example residential GHP system using a forced-air, HVAC energy-delivery system. Depending on the heat-pump design and system configuration, the GHP system could provide some or all of a building's hot-water demand, using heat removed from the building (during summer) or ground (at any time) as the energy source.

The installed capacity of GHP in the United States was 16,800 MW_{th} (or 4.8 million cooling tons)³⁵ as of 2016 (Lund and Boyd 2016). GHP use is more common in residential buildings than in commercial ones, based on a capacity ratio of 3.5:1 (Navigant 2013). About 75% of residential GHP applications are in new construction and 25% are retrofits of existing homes (Liu et al. 2019). GHPs represent about 1% of the U.S. HVAC market.

Figure 2-13 illustrates the distribution of GHP shipments throughout the United States in 2009,³⁶ with relevant climate zones indicated (EIA 2010).

2.2.4 Additional Value Streams

Geothermal energy can provide additional value beyond the electric or non-electric applications discussed in previous sections. First, the process of converting geothermal energy into electricity creates byproducts that can provide additional economic value streams. For example, the fluids processed through a geothermal power plant may contain minerals whose extraction and refinement could, under appropriate market conditions, add revenue beyond the sale of electricity. As an example, recoverable lithium carbonate from

³⁵ One cooling ton is equal to the amount of thermal energy required to melt one ton of ice in a 24-hour period (12,000 British thermal units/hour or about 3.5kW_{th}).

³⁶ The 2009 data reflected in Figure 2-13 are the last data available. EIA no longer tracks GHP shipments.

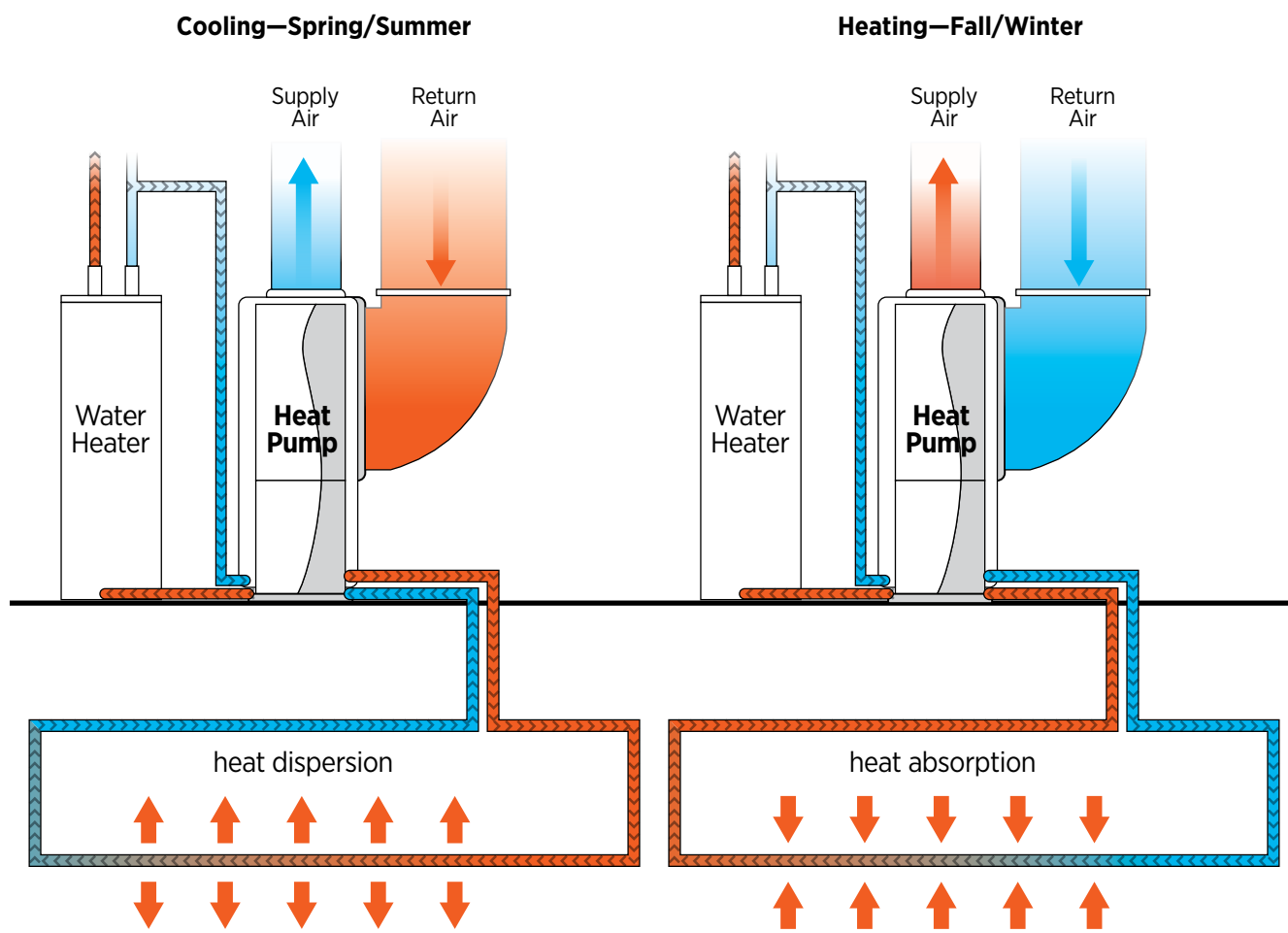


Figure 2-12. Schematic of a geothermal heat pump showing the simplified ground heat-exchanger loop, heat pump, and indoor delivery system
 Source: Modified from Water Furnace International, Inc. 2017

geothermal power production in the Salton Sea (California) has been estimated to be as high as about 170,000 metric tons annually (Neupane and Wendt 2017). At a 2017 annual average lithium carbonate price of \$13,900 per metric ton, this has the potential to supply the battery market with as much as \$2.3 billion annually in valuable materials (Neupane and Wendt 2017, Wendt et al. 2018, USGS 2018). In addition, geothermal resources can present value opportunities through integration with other energy-generation sources. Hybridizing and linking geothermal energy with other generation technologies can drive operational synergies and optimize the combined beneficial attributes of multiple technologies. In some cases, hybridization in the form of cascaded

energy uses and materials recovery from the geothermal resource can result in a whole that is greater than the sum of the individual parts.

The *GeoVision* analysis included evaluation of additional value streams as well as case studies to assess geothermal hybrid technologies likely to play a role in the future of geothermal energy. This analysis included an evaluation of geothermal resources hybridized with water desalination, solar energy, thermoelectric power generation (natural gas and coal), algal hydrothermal liquefaction, and compressed-air energy storage. These added-value assessments are detailed in Wendt et al. 2018.

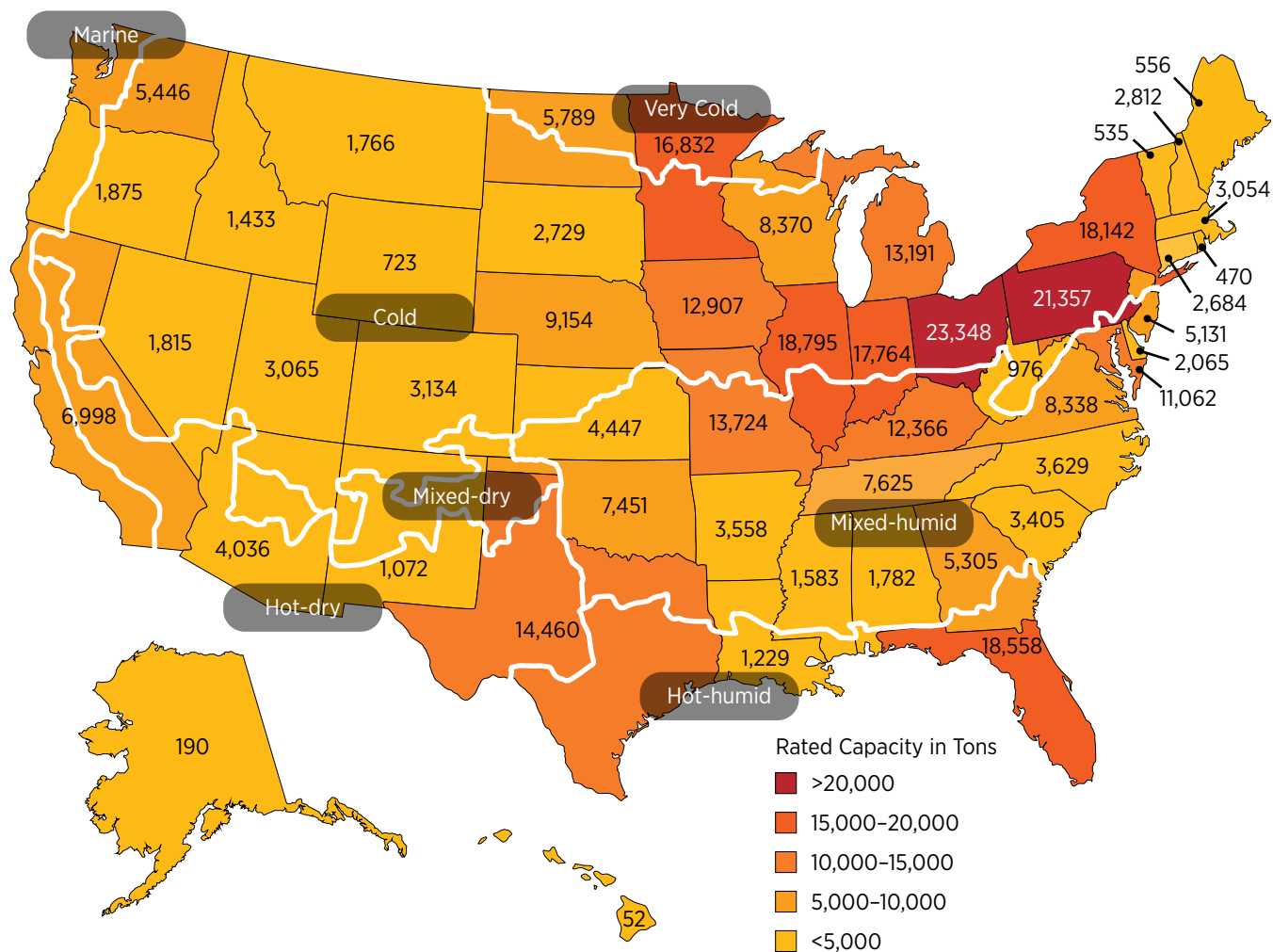


Figure 2-13. U.S. geothermal heat-pump shipments (rated capacity in cooling tons) in 2009

Source: Liu et al. 2018

Figure Note: The number in each state indicates the total capacity (cooling tons) of GHP shipments in 2009 in the state. The white lines indicate climate zones, which are based on the 2009 data on the destinations of GHP unit shipments in the United States and color-coded based on the total rated capacity (in cooling tons) shipped in that year (EIA 2010). The 2009 data are the last data available; EIA no longer tracks GHP shipments.

2.3 Geothermal Energy Benefits

Geothermal energy applications and resources possess characteristics that can appeal to a range of stakeholders. This section provides an overview of some of the beneficial characteristics of geothermal energy and its value to the nation.

2.3.1 Availability of National Geothermal Resources

The quantity and distribution of geothermal resources present enormous potential to provide nationwide, renewable, reliable, and resilient energy to the United States. Installed geothermal electric generation has historically been limited to the western United States (Figure 2-10). Improved technologies that reduce the costs of EGS development can broaden the geographic scope of geothermal power production to the national level. Deployment of geothermal direct-use applications also has the potential to grow across the country, as

communities realize the benefits of meeting local energy demands with geothermal district-heating solutions.

As noted in Section 2.1.3, GHP resources are vast and can be deployed virtually anywhere in America. Doing so would provide benefits to residential and commercial consumers through improved energy efficiency and cost savings, while also providing constant and quiet heating and cooling of residential and commercial buildings.

2.3.2 Economic Benefits from Geothermal Energy Generation

Geothermal power generation has positive impacts on local economies (Young et al. 2019, Millstein et al. 2019). Geothermal power plants provide direct financial benefits that are not typical of other renewable energy technologies. For example, geothermal power plants pay federal, state, and local royalties as well as property taxes, providing valued revenue streams in rural counties where these plants often operate. As with other energy projects, geothermal power plants also contribute to the labor market directly through jobs at the plants and indirectly by inducing employment in related supply-chain industries. Geothermal power plants and drilling technologies use a wide range of job skills and labor categories similar to those in fossil energy, mining, construction, manufacturing, and other industries. This shared skill base can allow workers to move easily across industries. The GHP industry demonstrates similar potential for market and job growth, including opportunities in manufacturing and installation. The economic benefits to the geothermal industry are discussed in Chapter 4.

2.3.3 Reliable Power Generation and Essential Grid Services

Reliable operation of the nation's electric grid requires a suite of essential reliability services that are best



Drilling and power-plant construction at the Blue Mountain geothermal field in Nevada. Photo credit: John Casteel

provided through a diversified portfolio of energy generation technologies (DOE 2017). Geothermal power plants can contribute to this diversification, providing several essential and ancillary grid services including regulation, frequency control, spinning reserve,³⁷ nonspinning reserve,³⁸ and replacement reserve (North American Electric Reliability Corporation 2011; North American Electric Reliability Corporation 2016). With appropriate market-pricing structures, geothermal power generation can operate flexibly, adapt to variability in the power system, and run in a load-following configuration. Geothermal power generation can also be incorporated into microgrid systems or provide black-start capabilities to recover from regional power outages during natural disasters or other emergency situations. This section describes some of the grid-service attributes of geothermal energy in more detail.

2.3.3.1 High Capacity Factor

The high (>90%) capacity factor³⁹ of geothermal energy means that geothermal power plants can operate 24 hours a day, with steady output nearly all of the time. The high capacity factor also means that geothermal power plants can generate about 2–4 times as much electricity as a wind or solar energy plant of the same installed capacity (Figure 2-14). For example, a

³⁷ Spinning reserve is additional, rapidly available capacity from generating units that are operating at less than their capability.

³⁸ Nonspinning reserve is additional capacity that is not connected to the electrical grid system but can be made available to meet demand within a specified time.

³⁹ Capacity factor is the unitless ratio of actual electrical energy output over a given period of time to the maximum possible electrical energy output over the same amount of time (Nuclear Energy Regulatory Commission 2017).

100-MW_e solar photovoltaic facility would generate electricity for fewer than 16,300 households (less than 200,000 megawatt-hours-electric [MWh_e]), whereas a wind energy project of the same capacity could generate electricity for around 37,000 households (about 400,000 MWh_e). By comparison, a geothermal power plant with the same nameplate capacity would produce enough electricity to power more than 74,000 households (about 800,000 MWh_e) (Cole et al. 2016).⁴⁰

2.3.3.2 Grid Reliability and Flexibility

Changes in the U.S. energy-generation mix and energy demands are altering how the electric grid operates. Utilities and system operators increasingly require generation sources that can balance changes in load and generation that occur throughout the day and across the seasons and ensure continued operation to meet the country's energy needs. An example of some of the challenges presented by this changing energy

mix has been documented in California (Text Box 2-3). Geothermal power plants can provide essential grid services and operate in a load-following mode, thus helping to support reliability and flexibility in the U.S. grid and ultimately facilitate a diverse, secure energy mix.

A 2017 study by Orenstein and Thomsen illustrates that the economic value of geothermal power remains relatively constant as its deployment increases, as compared to variable-generation sources. Orenstein and Thomsen assessed data from California and found that geothermal generation is worth \$32/MWh_e more than generation from solar photovoltaics on a combined energy and capacity basis. When considering the ancillary services and operational flexibility that geothermal can provide, the study finds that combined values can be more than \$40/MWh_e higher than solar photovoltaics.

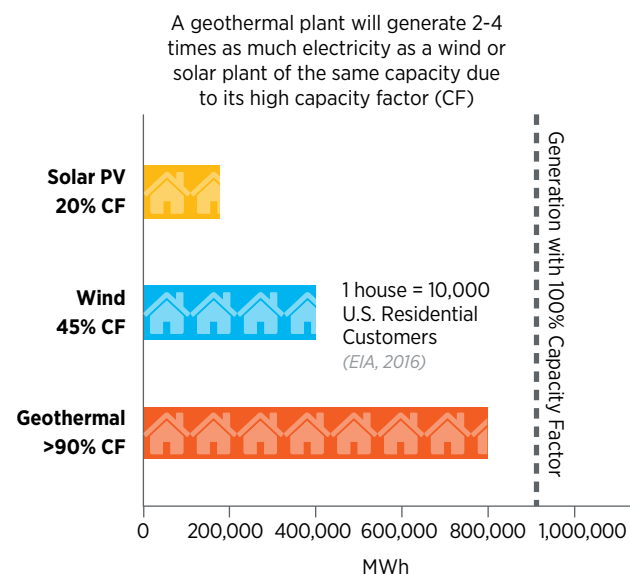


Figure 2-14. Capacity factors for geothermal, wind, and solar photovoltaic indicating annual generation (MWh_e) from equivalent 100-MW_e nameplate-capacity power plants

Source: EIA 2016b, Cole et al. 2016



Mosses thriving on ground altered by geothermal hot spring and fumarolic activity. Photo credit: Greg Rhodes

⁴⁰ Capacity factors for geothermal, wind, and solar were each selected as mid-level capacity factors from each of the technologies to be analytically agnostic and consistent, as detailed in the 2016 Annual Technology Baseline (Cole et al. 2016). For wind technologies, an average capacity factor of 45% from the middle technology resource group (TRG 5) was selected. For solar photovoltaic technologies, the mid-range capacity factor of 20% was selected, equivalent to a system in Kansas City. The geothermal capacity factor was selected for geothermal flash plants.

Text Box 2-3. Managing the “Duck Curve”

In California, initiatives such as the state renewable portfolio standard requiring 60% of retail electricity from renewable power by 2030—combined with available solar resources and rapidly declining levelized cost of electricity for solar (Cole et al. 2016)—have resulted in increased deployment of variable-generation renewable energy. As a result, new conditions have emerged, requiring operational changes to balance the grid (California Independent System Operator [CAISO] 2013, Denholm et al. 2015).

CAISO analyzed changing grid conditions to determine how real-time net electricity demand changes with policy initiatives. CAISO’s results indicate that, with growing penetration of renewables on the grid, there are higher levels of non-controllable, variable generation. As a result, the independent system operator must direct controllable resources to match both variable demand and variable supply (CAISO 2013). This is best illustrated through a review of net load profiles, which have the appearance of the industry-recognized “duck curve” (Figure 2-15).

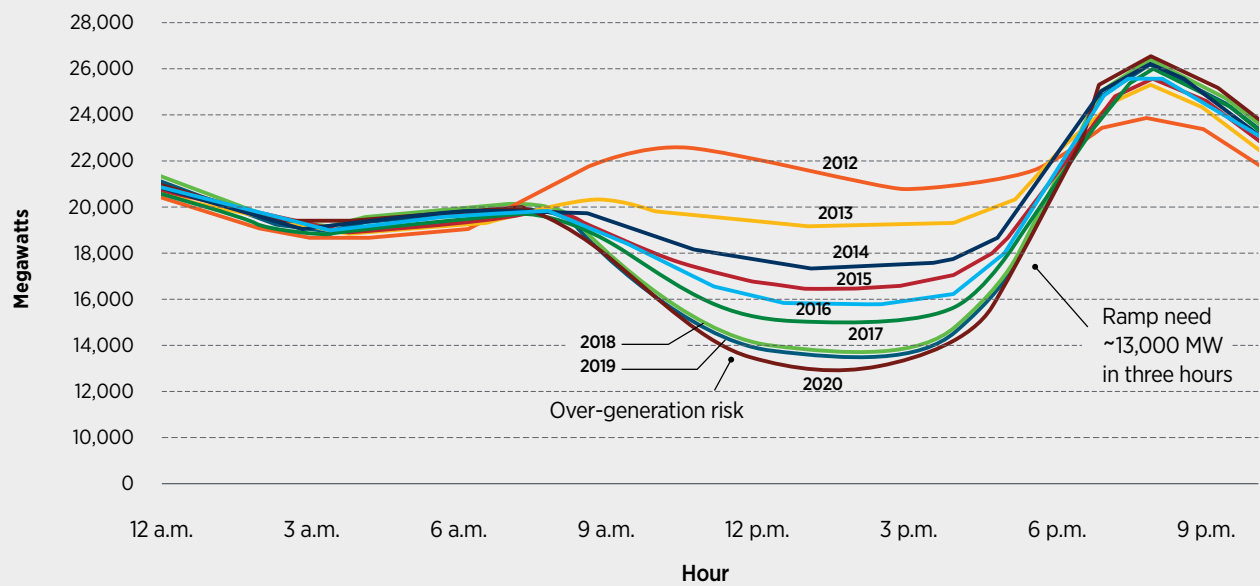


Figure 2-15. Past and projected net-load profiles to 2020 on a typical spring day in California, illustrating the “duck-curve” effect with steep ramping needs and over-generation risk

Source: CAISO 2013

The duck curve reflects an oversupply of energy in the middle of the day, sometimes resulting in negative pricing and curtailment (requirements to restrict generation) in the “belly” of the duck. As curtailment increases, the economic and environmental benefits of variable renewable generation decrease. In the case of increased solar curtailment, the overall benefits of additional solar could drop to the point where future installations are not economic (Denholm et al. 2015, Cochran et al. 2015).

As solar generation falls off toward the evening hours—when demand is rising—the result is a net load profile resembling the “neck” of the duck, with increased ramping and load-following requirements over ever-shorter time periods (projected to be 13 GW in three hours by 2020) (CAISO 2013). CAISO identified several essential grid services—such as frequency regulation, ramping and voltage support, and reserves—required to balance net loads and ensure grid reliability. Geothermal power plants are among the energy-generation technologies that can operate flexibly and provide services to help in balancing load and accommodating the deployment of an increasingly diverse energy-generation mix that includes more variable generation.

Flexible geothermal operations are the exception as of 2018 but have been demonstrated successfully by a few projects. The most notable example is the Puna Geothermal Venture facility (Hawaii), which generates 38 MW_e and is contracted to operate flexibly between maximum and minimum limits of 38 MW_e and 22 MW_e, respectively. Puna is considered a first-of-its-kind project that could be expanded to other facilities given appropriate contracts and retrofits (Text Box 2-4) (Nordquist et al. 2013). Geothermal power plants at The Geysers in California historically operated in traditional baseload, peaking, and load-following modes. Flexible generation at The Geysers was also offered to meet the needs of one of the utilities that was purchasing power from The Geysers (Cooley 1996, Matek 2015b).

Geothermal generation technology that can provide ancillary services is available for most operating geothermal power plants and examples such as Puna and The Geysers demonstrate utilization of those. However, market structures have not historically compensated most geothermal power plants to run as flexible, load-following generation. Although it is physically possible for a geothermal power plant to operate flexibly, doing so would not be cost effective under traditional power purchase agreements (PPAs). This economic barrier to widespread deployment of flexible geothermal power generation is elaborated in Section 2.4.

Text Box 2-4. Operational Flexibility at the Puna Geothermal Venture Plant

Power purchase agreements, or PPAs, are usually structured in a way that incentivizes geothermal power plants to run in a more traditional baseload configuration rather than providing flexible, load-following generation. In an exception, however, Hawaii Electric Light Company signed a PPA in 2011 with Puna Geothermal Venture for an 8-MW_e expansion, representing the first agreement for a fully dispatchable geothermal power plant (Nordquist et al. 2013). Based on the agreement, Puna Geothermal Venture receives a capacity payment and energy payments, making flexibility possible from an economic standpoint. This structure allows geothermal energy to participate in the grid's Automatic Generation Control, providing the utility with the unique ability to remotely direct the net output of the Puna Geothermal Venture facility and dispatch renewable generation, 24 hours a day. This functionality helps enable balancing of changing load and generation throughout the day, including variable generation and its uncertain output. Immediate benefits include lower energy rates to Hawaii Electric Light Company's customers, reducing Hawaii's dependency on imported fuels, maintaining reliability, and optimizing the geothermal resource (Nordquist et al. 2013).

In 2018, eruptions of the Kilauea volcano on Hawaii's Big Island affected Puna Geothermal Venture and forced a shut down. The plant operator was able to implement contingency plans that protected the geothermal steamfield and power plant from the worst effects; lava covered three of the plant's 11 geothermal wells and burned a substation and adjacent warehouse. At the time of *GeoVision* report publication, Puna Geothermal Venture remained inoperable. The plant operator has indicated that work is underway to resume operation of the plant and estimates it will be ready for operation by year-end 2019 (Ormat Technologies 2019). The 60-MW_e Krafla geothermal field in Iceland was similarly affected during a series of eruptions from 1975 to 1984 and eventually returned to full generation (B.M. Júlíusson et al. 2005).

2.3.3.3 Grid Security via Black-Start Capability

To come online and start providing energy to the grid, power plants typically rely on other, external sources of electricity to power startup units and control equipment. “Black start” is the ability to restart a power-generation unit without relying on such external electricity (e.g., in the event of a blackout) (DOE 2015). The black-start process essentially coordinates the restarting of designated resources that can energize the transmission system enough to bring other generators online and return the system to operation (Torres 2018).

Geothermal power plants can support black-start capability by functioning as microgrids that provide generation to a power plant or portion of the electric grid without external electricity. Geothermal plants can also quickly reduce generation to meet only the load conditions essential for internal plant operations, run in that minimum condition for extended periods of time, and then ramp quickly (usually in less than five minutes) to full load to supply power back to the grid and restore other generation plants that lack the capability to black start (Tucker 2017).

2.3.3.4 Fuel Security

Geothermal energy is intrinsically secure because it uses a resource that is onsite, reliable, and not subject to fuel-price volatility or surface climate conditions. Unlike other energy resources that are constrained by weather patterns or thermal generators that depend on fuel supply chains, the production of geothermal fluids from the subsurface is continuously available for power generation and geothermal direct-use applications. Geothermal power plants also effectively purchase the entire life-cycle fuel supply up front because this supply is built into the initial capital costs for drilling out the wellfield. The result is the availability of a sustainable, renewable, and practically inexhaustible fuel supply when appropriately managed (Sanyal 2010, Lowry et al. 2017).⁴¹

Geothermal energy is intrinsically secure because it uses a resource that is onsite, reliable, and not subject to fuel-price volatility or surface-climate conditions.

2.3.4 Environmental and Efficiency Benefits

Geothermal energy developments offer environmental and efficiency advantages relative to other energy sources. The design of binary geothermal power systems achieves nearly 100% geofluid injection, which virtually eliminates emissions. Geothermal power production is also one of the cleanest energy generation technologies, with very low emissions of sulfur dioxide, nitrogen oxides, and fine particulate matter. For example, on a per-MWh_e basis, flash geothermal power plants emit less than 4% of the sulfur dioxide of conventional coal plants and virtually none of the nitrogen oxides or fine particulate matter (Kagel et al. 2007).

In the United States, geothermal electricity generation annually offsets the equivalent of 22 million metric tons of carbon dioxide, 200,000 tons of nitrogen oxides, and 110,000 tons of particulate matter from conventional coal-fired plants (Green and Nix 2006). Geothermal energy production also requires a smaller land footprint compared to many other energy-generation technologies (Figure 2-16)—404 m² per GWh_e, which is less than coal (3,642 m²), wind (1,335 m²), or solar photovoltaic (3,237 m²) (Kagel et al. 2007).

With improved technologies enabling cost-effective EGS development, geothermal direct-use applications have the potential to supply vast amounts of the country’s industrial, commercial, and residential heating from geothermal district-heating systems. GHPs are superior to traditional HVAC solutions in terms of energy efficiency and the ability to provide a quiet, zero-emission heating and cooling solution with high reliability and long system life.

⁴¹ The typical length of a standard PPA is 30 years. This time frame is not necessarily coupled to geothermal reservoirs/resources, which can run for centuries (if not longer) when sustainably managed (Sanyal 2010, Lowry et al. 2017). In many instances, considerable geothermal resources are located in close proximity to U.S. Department of Defense facilities, such as military bases. The intrinsically secure attributes of geothermal resources could offer an unmatched level of reliability to military installations that is critical to national security (Sabin et al. 2004).

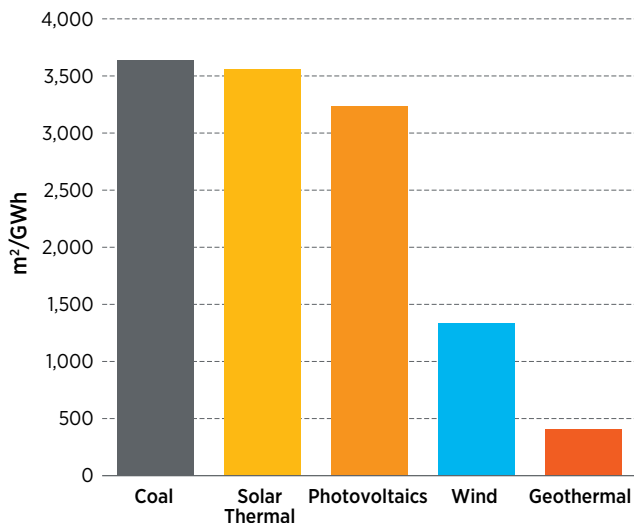


Figure 2-16. Land footprint by GWh_e for various electricity-generation technologies

Source: Kagel et al. 2007

Figure Note: Coal includes mining. Photovoltaics (solar) assumes central-station photovoltaic projects, not rooftop systems. Wind reflects land occupied by turbines and service roads.

All types of buildings, including homes, office buildings, schools, and hospitals, can use GHPs. ENERGY STAR-certified GHPs have minimum coefficients of performance⁴² higher than those of conventional residential space heating and cooling equipment; higher coefficients of performance equate to electricity savings and lower operating costs.⁴³ GHPs eliminate on-site combustion of natural gas or other fossil fuels for space and water heating as well as the associated emissions. Considering savings in both electricity and fossil fuels, GHPs consume 20%–40% less primary (source) energy than conventional heating/cooling systems. GHPs use some electricity to operate, which is typically primary energy from the grid.

Savings from GHP systems come with a trade-off in higher upfront capital costs for the systems, highlighting the importance of payback periods and innovative business models and financing that can reduce the financial burden and risk for consumers. The installation price of a GHP system can be several times that of a conventional heating and cooling system of

the same capacity; however, the additional cost is returned in energy savings within 5–14 years (Hughes 2008). If financed, consumer savings can be realized immediately because the financing payments can be offset by the savings in electricity consumption provided by the GHP system (Figure 2-17). System life is estimated to be longer than 24 years for the heat-pump components and more than 50 years for the ground heat-exchange loop (American Society of Heating, Refrigerating and Air-Conditioning Engineers 2011).

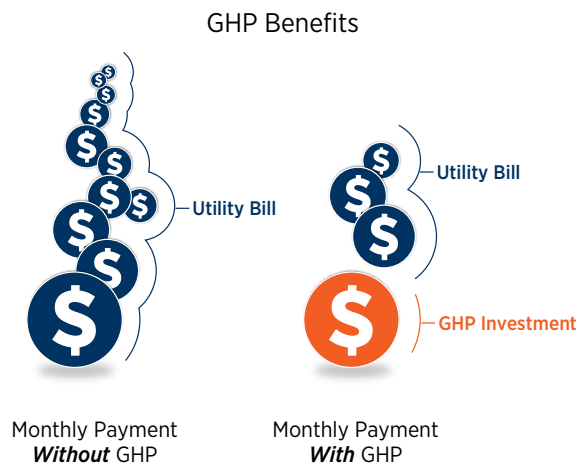


Figure 2-17. A conceptual illustration of potential consumer savings with geothermal heat pumps

2.4 Technical and Non-Technical Barriers to Geothermal Development

Although domestic geothermal use has been growing for decades, the U.S. geothermal industry has realized only modest technology deployment and consumer adoption. For example, U.S. geothermal electricity generation increased only 6% between 2008 and 2015, and, as of 2017, represented only 0.4% of total U.S. electricity generation (EIA 2016). By comparison, wind and solar generation increased 240% and 2,700% over the same time period and now comprise 5.6% and 0.9% of total U.S. generation, respectively.

⁴² The coefficient of performance refers to the ratio of useful heating or cooling provided to the work required. Electricity savings and coefficients of performance are related through the following equations: Electricity Savings = (P1-P2)/P1, where P1 is the electricity consumption of a GHP unit and P2 is the electricity consumption of a heating/cooling unit against which the electricity savings are to be compared (e.g., traditional HVAC system such as an air conditioner, gas furnace, boiler). Electricity consumption of P1 and P2 are determined by dividing the heating or cooling demand by the unit's coefficient of performance.

⁴³ GHPs have coefficients of performance of 3.1–4.1 for heating and 4.7–6.2 for cooling, depending on various applications (ENERGY STAR 2017).

Modest growth in geothermal deployment is not a result of limited geothermal resources because, as discussed in Section 2.1, geothermal resources are vast and geographically dispersed. Instead, other factors are responsible for the slow growth of geothermal deployment. Technical and non-technical challenges in resource exploration, drilling, and development present fundamental barriers to improved economic capture of geothermal resource potential. This topic was analyzed in the *GeoVision* analysis and is detailed in Lowry et al. 2017, Doughty et al. 2018, Augustine et al. 2019, McCabe et al. 2019, and Young et al. 2019.

The results of the *GeoVision* analysis illustrate that, if the industry continues along business-as-usual projections, geothermal resources and technologies will remain a relatively small niche player in the energy sector. Modeled results and impacts of the *GeoVision* analysis are summarized in Chapters 3 and 4 and indicate that, under existing conditions, geothermal technologies will continue to achieve only limited rates of market penetration—thus failing to capture the myriad of benefits that geothermal energy can offer to the nation.

The *GeoVision* analysis evaluated key factors that influence deployment for the electric and non-electric sectors. For both sectors, this analysis includes factors such as the state of the technology, geographic applicability or co-location of the resource availability and energy demand, financing and market conditions, and industry outreach and basic public awareness. For the electric sector, additional key factors of importance include land access and regulatory timelines.

This section divides barriers examined in the *GeoVision* analysis into technical and non-technical groups. Those groups are subcategorized based on barriers by application (electric and non-electric sectors) and further subdivided by resource type (conventional hydrothermal vs. EGS) for barriers within the electric sector. Several barriers affect more than one application or resource, and many of the solutions for technical barriers result in lowered risk and costs, which—in turn—affect non-technical barriers such as obtaining financing. The complexity of geothermal barriers presents operators and researchers with challenges to wider deployment as well as opportunities for

innovation. The *GeoVision* Roadmap (Chapter 5) discusses a number of actions aimed at pursuing such innovations and overcoming barriers. Achieving those actions will reduce costs and ultimately make large increases in geothermal deployment cost effective.

2.4.1 Technical Barriers: Electric Sector

Technical barriers to deployment of geothermal resources for electricity generation are mainly a result of geothermal energy's unique characteristics as a subsurface resource. This attribute stands in marked contrast to other sources of renewable energy; whereas wind, hydropower, biomass, and solar resources are immediately accessible at the Earth's surface, geothermal resources are not.

Exploring, discovering, developing, and managing geothermal resources is an inherently complex endeavor that carries greater fundamental risks and upfront costs compared to other renewable energy technologies. Geothermal resources are identified, assessed, and targeted using complex geophysical and geological techniques, often referred to as pre-drilling activities.⁴⁴ These activities directly guide subsequent resource access and confirmation, which requires invasive, costly, and high-risk drilling. Managing risks and costs during exploration drilling and the resultant drilling success ultimately depends on the degree to



Drill bits used at the Raft River geothermal site in Idaho.
Photo credit: K.T. Hanna

⁴⁴ Pre-drilling exploration activities are non-invasive and do not penetrate the surface through drilling. Such activities often include, but are not limited to, geological and structural mapping studies, remote-sensing data acquisition, geophysical surveys such as magnetotelluric or seismic data acquisition, and geochemical surveys.

which non-invasive (non-drilling) exploration technologies can characterize the geothermal resource. There are no existing exploration technologies that—on their own—can produce the improvements in drilling success and cost reductions necessary to trigger growth in geothermal resource deployment beyond historically modest trajectories. Instead, it is likely that new approaches to integrating existing technologies—as well as an entirely new class of innovative exploration technologies—will need to be developed to produce the required drilling success rates and cost reductions.

The costs of pre-drilling and exploration drilling activities are comparatively small with respect to overall development costs; however, they directly influence subsequent drilling success rates and thus have a major financial impact on projects. In a 2016 analysis, Wall and Dobson found that exploration drilling results led to drilling full-sized⁴⁵ development wells less than one-third of the time. Exploration, confirmation, and development-well drilling collectively account for 30%–50% of the costs of geothermal development (Bromley et al. 2010). The cascading effects of exploration activities—from pre-drilling geotechnical studies through exploration, confirmation, and development drilling—have a collective impact on overall project costs and success. The limitations of existing technologies that support these activities present significant technical barriers to geothermal development. Sections 2.4.1.1 and 2.4.1.2 discuss these limitations, and the *GeoVision* Roadmap includes research and development actions aimed at overcoming them.

2.4.1.1 Hydrothermal Resources

As operators expand the U.S. geothermal power base, they have encountered increasing technical challenges in conventional hydrothermal resource availability. The principal barrier is a lack of adequate exploration and drilling technologies that can reliably find and delineate new resource targets.

Conventional hydrothermal resources exist as both identified and undiscovered systems (Section 2.1). Until only recently, all geothermal power developments have been supported by identified hydrothermal resources, which have provided electricity generation in the western United States since 1960. Of the 9 GW_e of identified hydrothermal resources, roughly 3 GW_e have already been developed,⁴⁶ meaning that the majority of the remaining conventional hydrothermal resource potential is the 30 GW_e of undiscovered hydrothermal systems estimated by the U.S. Geological Survey (Williams 2008b). Undiscovered hydrothermal systems do not have surface manifestations such as geysers, hot springs, or fumaroles to indicate their presence. Available data indicate that undiscovered hydrothermal resources exist, and some have been discovered and economically developed—e.g., the Don A. Campbell geothermal power plant (Nevada) (Orenstein and Delwiche 2014) and the McGinness Hills geothermal power plant (Nevada) (Nordquist and Delwiche 2013). By definition, however, the majority of undiscovered conventional resources have yet to be identified and confirmed.



Looking southeast along Big Sulphur Creek canyon with the McCabe geothermal power plant in foreground (The Geysers in California). Photo credit: Karl Urbank and Earl Holley

⁴⁵ For the purposes of the *GeoVision* analysis, full-sized wells are considered those with an 8.5" or larger bottom-hole diameter.

⁴⁶ Some of the remaining *identified* hydrothermal resources are uneconomic to develop due to a combination of technical barriers that include insufficient size, temperature, and permeability, so that the amount of commercially competitive identified hydrothermal resources is even smaller. Of the remaining 6 GW_e of identified geothermal resources, nearly 2 GW_e of developable geothermal resource potential have been identified at the Salton Sea Geothermal Field in California (Gange et al. 2015).

The limitations in existing exploration technologies add significant time and risk to geothermal developments overall. This barrier is reflected in increased project financing and development costs, thus linking to and compounding financial barriers to geothermal developments. Geothermal exploration and drilling technologies have historically been developed for exploring *identified* resources, not *undiscovered* resources. Beyond the improvements necessary to better explore for identified resources, a new class of exploration technologies will be required to identify, delineate, target, and develop undiscovered conventional resources in a cost-effective manner. Details about these limitations and opportunities are discussed in Doughty et al. 2018.

Once conventional geothermal systems are developed, continued project success relies on cost-effective, sustainable, long-term resource and asset management. Overcoming the technical barriers to this objective requires tackling complex issues, a factor rolled into long-term operating costs and reflected in the high initial costs of geothermal development. Long-term geothermal resource and asset management can be improved through new technologies in data collection, monitoring, modeling, and assessment, all of which can ultimately improve project economics. These topics are discussed in Lowry et al. 2017.

2.4.1.2 Enhanced Geothermal Systems

The principal technical barrier to EGS resource development is that the subsurface must be engineered so that heat can be extracted economically for power generation or direct-use applications. This task is extremely challenging, especially for deep-EGS resources, given a starting resource condition that might contain heat but no practical means for extraction of that energy resource.

EGS development draws some parallels to unconventional oil and gas development⁴⁷ in that each requires creating and sustaining a functional resource by using reservoir stimulation technologies. However,

Under existing conditions, geothermal technologies will continue to achieve only limited rates of market penetration and will fail to capture the myriad of benefits that geothermal can offer to the nation. The results of the *GeoVision* barriers analysis illustrate that if the industry continues along business-as-usual projections, then geothermal resources and technologies will remain a relatively small niche player in the energy sector.

the ultimate goal of reservoir creation in EGS is unique. In unconventional oil and gas, the high energy density of hydrocarbons supports cost-effective creation of a limited reservoir volume and extraction of a relatively low cumulative volume of oil or gas from near the wellbore. This extraction occurs under short-lived, high initial-production conditions, followed by rapid production declines. By contrast, an EGS reservoir requires sustained *circulation* of high flow rates of water over long periods of time, requiring large reservoir volumes.

In oil and gas, the cost of a well may be recovered in a matter of just months, with subsequent production yielding profit after comparatively minimal operational and maintenance costs. The economic conditions constraining EGS, by contrast, are fundamentally different due to the comparatively low energy density of hot water. EGS wells will need to support the extraction of this lower-energy-density hot water over payback periods on the order of a decade (Glacier Partners 2009). These technical realities drive a requirement for volumetrically large reservoirs with distributed fractures that support efficient heat exchange and can be sustained over long periods of time.

An entirely new class of reservoir stimulation technologies may be required to achieve EGS development. These technologies are likely to involve a combination of 1) high-pressure reservoir stimulation, coupled with chemical-treatment technologies

⁴⁷ “Unconventional resources” is an umbrella term that refers to, “oil and natural gas that is produced by means that do not meet the criteria for conventional production” (EIA Glossary n.d.). Under existing technical and economic conditions, tight oil resources are considered a major subset of unconventional oil and gas resources (EIA 2018). Tight oil resources are defined as those produced from petroleum-bearing formations with low permeability that must be stimulated to produce oil at commercial rates (e.g., the Eagle Ford, the Bakken Formation).

adapted from the oil and gas industry; and 2) low-pressure stimulation techniques that have been shown to be effective in DOE's in-field and near-field EGS demonstration projects. These topics, as well as the assumptions of exploration and drilling technology improvements incorporated into the *GeoVision* analysis, are detailed in Lowry et al. 2017, Doughty et al. 2018, and Augustine et al. 2019.

2.4.2 Technical Barriers: Non-Electric Sector

Technical barriers to deployment for non-electric geothermal uses are similar to those for geothermal electricity generation. As is true for electric-sector uses, geothermal district heating and GHPs are both impacted by high upfront costs and technology limitations; in particular, district-heating applications face challenges related to retrofitting older heating systems. Challenges for non-electric uses tend to be less technically complex, but these uses face complexities relating to their direct interplay with consumer markets. In the case of district heating, geographical alignment of resources with market-demand centers is a key limiting factor for development.

2.4.2.1 Geothermal District Heating

Similar to EGS resources in the electric-power sector, high upfront costs associated with EGS resource development for district-heating potential could severely restrict its economic deployment. The same technology improvements that could lower EGS costs and increase resource deployment in the electric-power sector would similarly impact the ability to deploy district-heating applications for this resource. The economic deployment of geothermal district heating is also limited geographically because district heating requires suitable resources to be co-located with populated areas (demand centers). Because most conventional hydrothermal resources are located in rural areas throughout the western United States, deployment potential is limited with existing technologies. Enabling cost-effective development of EGS resources through technology improvements can reduce geographic limitations on geothermal district heating.

Beyond the subsurface technology barriers related to economic EGS development, some relatively minor technical barriers extend to the surface. These barriers relate to technology adaptation across a range of systems with differing requirements and infrastructure. The large diversity in heating and cooling systems across the United States can complicate and increase the costs of retrofitting older systems.

2.4.2.2 Geothermal Heat Pumps

GHPs are cost-effective, mature technologies that have been in existence for decades but remain a niche application. Although GHP systems can be less expensive in the long run, the cost of ground



Installation of a horizontal closed-loop ground heat exchanger for a geothermal heat-pump system. Photo credit: Ed Lohrenz/
International Ground Source Heat Pump Association

heat-exchanger loops frontloads the cost burden for consumers and impedes wider adoption of GHP systems. Technology advances in drilling efficiency and system performance are slow to develop and have yet to reduce upfront costs in a significant way. Streamlined and/or innovative business models that eliminate or offset these upfront technical costs for consumers have not been developed fully or gained traction in the heating and cooling market.

2.4.3 Non-Technical Barriers

Technical barriers—and some non-technical barriers—vary among geothermal resources and applications. However, because of their subsurface nature, all

geothermal resources share one key non-technical barrier: lack of awareness and acceptance. Wind, solar, and hydropower generation technologies are generally self-evident: wind turbines, solar panels, and hydroelectric dams are large, familiar structures that provide tangible evidence of the use of those natural resources. In contrast, the public is generally unaware that geothermal resources exist and could be used for a wide array of applications. The most publicly recognized examples of geothermal resources are erupting geysers, such as Old Faithful in Yellowstone National Park or natural hot springs often associated with resorts and spas. Those features are visible and recognizable, but that alone does not readily convey the vast potential to harness geothermal resources for energy on a national scale.

Where geothermal resources are used by power plants, geothermal direct-use applications, or GHP systems, the installations tend to be overlooked by the public; solar panels on a rooftop advertise the technology to passersby, whereas a GHP installation is effectively invisible. Geothermal energy infrastructure is generally low profile and has a small surface footprint, and it often blends into the surrounding environment. Although these attributes are often beneficial to geothermal stakeholders, they also contribute to low levels of awareness about geothermal energy—in turn creating a barrier to geothermal deployment.

Success in geothermal development depends in part on the attitude of affected stakeholders, including members of the public, policymakers, and market participants (Pellizzoni 2010, Reith et al. 2013).

Awareness and acceptance can influence policies, incentives, land access, and other features crucial to geothermal development. In fact, many barriers to successful renewable projects at the implementation level can be considered manifestations of a lack of social acceptance (Wüstenhagen et al. 2007). For example, the public may not have a clear understanding of EGS projects and/or induced seismicity, which could lead to lower acceptance for future EGS projects.

Research on social acceptance for geothermal projects has mostly occurred internationally, such as in Europe (e.g., ENGINE 2007, Leuch et al. 2010, Reith et al. 2013, Pellizzone et al. 2015), Australia (Dowd et al. 2010, Romanach and Carr-Cornish 2013), Indonesia (Shoedarto et al. 2016), and Japan (Kubota 2015). Pellizzone et al. (2015) looked at social acceptance of geothermal energy in Italy and concluded that the public’s awareness of and optimism for geothermal was much lower than that for solar and wind energy (Figure 2-18).

In contrast, the extensive U.S.-specific data on social acceptance has focused primarily on other renewable technologies, such as solar and wind (e.g., Lago et al. 2009, Tegen and Lantz 2012, International Energy Agency Wind 2013, Hoen 2015, Pattern Development 2015). One U.S.-based study that was directly related to geothermal energy was a 2005 analysis that focused on public comments about National Environmental Policy Act (NEPA) documents for eight geothermal project sites. The comments were assessed to provide a sense of the level of public input and primary areas of concern. Comments most often came from agencies,

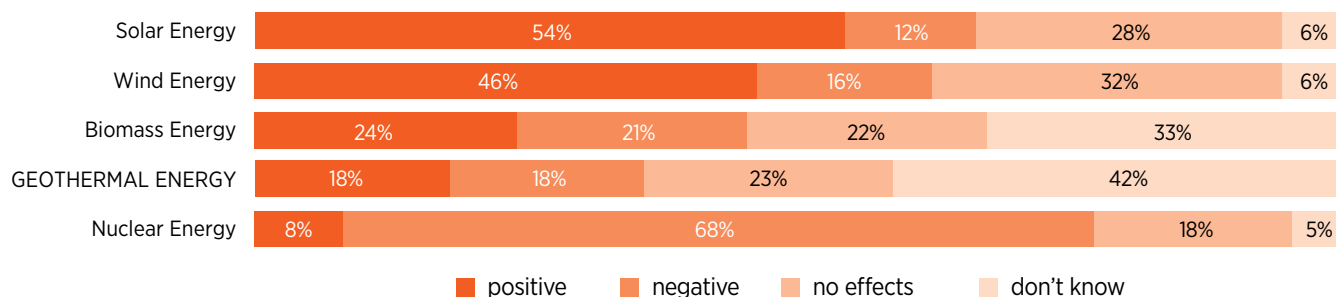


Figure 2-18. Acceptance of renewable energy technologies based on a social acceptance survey conducted in Italy by Pellizzone et al. (2015)

Figure Note: Results show that, in Italy, solar and wind energy technologies are more accepted than geothermal, despite Italy having the first operating geothermal power plant in the world (Larderello, operating since 1911 in Southern Tuscany).



Drilling a 9,000-foot geothermal test hole in Fallon, Nevada.
Photo credit: Andrew Tiedeman

special interests (e.g., homeowners' associations), or environmental groups, and frequently indicated a lack of knowledge of geothermal development. Project opposition can be minimized where outreach efforts, including education and interaction with interested parties, occur at an early stage (Heitter et al. 2005).

Also central to analyzing non-technical barriers is acknowledging the roles that federal and state governments play in the energy sector. These roles include promoting domestic industry; maintaining national security, including energy security; ensuring residential and workplace safety; enforcing legal and transparent business operations; regulating public/private entities such as utilities or co-ops; protecting the environment; supporting the responsible management and development of national resources; and collecting revenue to maintain and improve infrastructure and to support critical government functions.

2.4.3.1 Non-Technical Barriers: Electric Sector

In addition to the lack of social acceptance already noted, the geothermal electric sector is strongly impacted by other non-technical barriers. A 2016 study examining 6.4 GW_e of U.S. geothermal electricity projects under development from 2012–2015 concluded that the largest barriers included 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).

To evaluate opportunities for increasing geothermal deployment and/or optimizing project development timelines, the *GeoVision* analysis assessed barriers related to market conditions, land access, lease processing, permitting, and associated regulatory reviews. The analysis integrated feedback from an expert team comprising relevant government agency and industry representatives. The analysis, assumptions, and applications are discussed in Chapter 3 and detailed further in Augustine et al. 2019 and Young et al. 2019. This section provides a summary of non-technical barriers considered for the electric sector in the *GeoVision* analysis.

Power Purchase Agreement Acquisition and Other Market Barriers

Utility Procurement Practices: Established utility procurement practices, including those for PPAs, have not historically reflected some benefits of geothermal power. Existing renewable energy procurement 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 (Linville et al. 2013, EIA 2015). Additional grid integration costs associated with various technologies, such as added transmission capacity or additional power needed to balance the load, are often not taken into account in levelized cost calculations, nor are the costs and impacts from the risks associated with volatile fuel prices. These factors can result in additional, unplanned costs on power suppliers as well as on the supply

grid, reducing the efficiency and cost effectiveness of the U.S. electric grid. Levelized cost of electricity calculations that do not account for the benefits of geothermal power in these areas are a barrier to geothermal deployment.

Asset Flexibility: Geothermal power plants have traditionally operated for baseload power. Advancements in power plant and control technology, however, now allow geothermal plants to operate in grid-support and load-following modes to provide spinning reserve, non-spinning reserve, regulation reserve, and replacement or supplemental reserve. The future electricity grid is projected to have greater penetration of variable generation energy resources such as wind and solar and will increasingly require power-generation technologies that can operate flexibly. As indicated in Section 2.3.3.2, two key examples of geothermal power plants that have provided this flexibility are The Geysers in California and Puna Geothermal Venture in Hawaii (Text Box 2-4).

For most geothermal power plants, the barrier to flexible operation is economic rather than technical, although technical barriers compound and complicate the issue.⁴⁸ A 2014 industry survey of geothermal power developers confirms that the primary reason most geothermal power plants do not operate as flexible sources of electricity is because economic considerations are insufficient to ensure an acceptable return on investment. Although it is physically possible for geothermal power plants to operate flexibly, doing so would not be cost effective under traditional PPA contract terms. PPAs that incentivize geothermal plants to operate flexibly have not historically been offered (Matek 2015b). PPA terms would need to be modified in order for geothermal power plants to be compensated for operating as a reserve and flexible facility instead of as baseload power.

Two innovative principles that could be incorporated into future geothermal power contracts to encourage flexible operation are: 1) contracts that include payment schedules defining the price of power in response to a dispatch signal transmitted by the independent system operator or other load-serving entity; and 2) increased



Sunset over the Vulcan and Hoch geothermal power plants at the Salton Sea geothermal field in California. Photo credit: Alexander Schriener, Jr.

ability of geothermal plants for frequency regulation (i.e., ramping generation assets up or down over a period of a few minutes) through power pricing that includes payments specifically for frequency-regulation services (Matek 2015b, Edmunds and Sotorrio 2015).

Edmunds and Sotorrio (2015) studied ancillary service revenue potential for geothermal generators in California and found that prices for geothermal energy sales from existing PPAs are significantly higher than average ancillary service prices in California. As such, there is little incentive for developers to seek contracts that compensate for ancillary services in lieu of energy sales. As more variable-generation capacity comes online and the value of flexible generation increases, the incentive to develop such contracts may also increase.

Federal and State Incentives: Congress has enacted a range of federal tax and subsidy policies—including the Investment Tax Credit and the Production Tax Credit—to support the development of both renewable and fossil fuel energy. However, the structure and duration of federal incentives compared to long geothermal development timelines make it difficult for developers to rely on such incentives (Young et al. 2019). For example, the Production Tax Credit has rarely been guaranteed to be in effect for longer than five years, and geothermal exploration and development timelines are typically longer than this.⁴⁹

⁴⁸ When a geothermal power plant ramps up or down to provide flexibility, either the production must be variably throttled and cycled at the wells, or continuous production from wells must variably bypass the plant and be diverted to injection or to a cascaded energy-use scheme. Geothermal well cycling can damage wells and reduce operational lifespan. Flexibility introduced either at the wellhead or through diversion at the power plant can introduce significant operational complexity and cost.

⁴⁹ Geothermal systems qualify for the Investment Tax Credit, which was first passed in 2005. The Investment Tax Credit policy has been extended and modified several times. As of the 2016 changes in the Consolidated Appropriations Act (passed in December 2015), geothermal electricity systems are eligible for a 10% credit with no expiration date (as of the time of this report), based on the date of the start of service.

Many states have also enacted policies to support the development of renewable energy. State policies include renewable portfolio standards and other programs that require a certain amount of electricity to be purchased from renewable sources. Some of these policies may include set-asides to incentivize specific renewable technologies; these set-aside programs have been successful in supporting the development of solar and wind energy projects, but they have not been used to support geothermal development.⁵⁰ Limited geothermal generation has been procured under state renewable portfolio standards (Lofthouse et al. 2015). For example, more than 12.5 GWe of renewables were procured under California's renewable portfolio standard from 2003 to 2013, yet only 100 MWe (less than 1%) were from geothermal power (Lofthouse et al. 2015).

Permitting/Land Access: Development Timelines

Federal Lease Processing: Regulatory agency staff funding and/or availability to approve and process geothermal lease nominations may extend development timelines, particularly when involving a separate federal surface land management agency that must provide a “concurrence” to authorize the Bureau of Land Management (BLM) to lease the subsurface geothermal resource. Geothermal lease nominations for projects proposed on federal surface lands not managed by the BLM must receive approval from the surface land management agency (43 CFR § 3201.10(a)(2)) and complete an environmental review process under NEPA for both the surface land management agency and the BLM (generally in the form of a single NEPA review) before the BLM can conduct a lease sale.⁵¹ In practice, this period lasts 1–4 years and is assisted by tiering⁵² to the 2008 Geothermal Programmatic Environmental Impact Statement.⁵³

As an example, the U.S. Forest Service has previously experienced a backlog of geothermal lease nominations. The Energy Policy Act of 2005 (EPAct

2005)⁵⁴ established requirements for a program to reduce the backlog of Forest Service geothermal lease nominations by 90% within a 5-year period (EPAct 2005, Sec. 225). As of 2014, the BLM and the Forest Service had expended all funding under EPAct Sec. 225 and successfully completed processing the backlog of geothermal lease nominations.

However, the possibility that geothermal lease nomination backlogs could occur again in the future remains. Funding for geothermal activities requiring Forest Service approval is included in the agency's minerals and geology line item,⁵⁵ which historically has accounted for less than 1% of the Forest Service annual budget (Witherbee et al. 2013). In addition, geothermal activity⁵⁶ is taking place in less than 10% of National Forests (11 of 154), resulting in competition for Forest Service staff time and resources. Although not unique to geothermal, firefighting and other development activities (e.g., timber harvesting) generally have received priority in department-level staffing and budgeting decisions. As a result, limited staff time is available to review geothermal lease nominations and can prevent the associated lands from becoming available for leasing for an extended period of time.



A plant chemist samples silica concentrations from a geothermal injection brine line. Photo credit: Jeff Winick/Allegheny Science and Technology

⁵⁰ State renewable portfolio standards generally do not have specific requirements or set-asides for geothermal generation similar to those often applied to other forms of renewable generation, primarily solar.

⁵¹ The BLM administers geothermal lease sales on federal land, although both the Bureau and the surface-managing agency must satisfy NEPA requirements.

⁵² Tiering refers to “the coverage of general matters in broader environmental impact statements (such as national program or policy statements) with subsequent narrower statements or environmental analysis...incorporating by reference the general discussions and concentrating solely on the issues specific to the statement subsequently prepared” (40 CFR § 1508.28).

⁵³ The Geothermal Programmatic Environmental Impact Statement helped to reduce time from geothermal nomination to lease sale (BLM and U.S. Forest Service 2008).

⁵⁴ Energy Policy Act of 2005 (Pub. L. 109-58). 199 Stat. 594.

⁵⁵ The Forest Service does not have a geothermal-specific budget line item to provide concurrence for geothermal lease nominations.

⁵⁶ Geothermal activity refers to an expressed interest in leasing, an active lease, or installed wells or generating facilities.

Federal Permit Review and Processing: Geothermal development is also subject to timelines in the review and processing stages in federal permitting. Federal and state permitting office staff have a range of experience and varied processes. At the federal level, field offices in areas that already have geothermal projects often have federal leasing and permitting staff who are familiar with geothermal development, but staff in areas without geothermal projects can lack the experience necessary to process new geothermal applications. Delays can also occur in locations with experienced staff when geothermal experts are unavailable due to competing priorities or other reasons.

Multiple Environmental Reviews and the National Environmental Policy Act: The length and number of environmental reviews for a single geothermal project can impact geothermal deployment (Young et al. 2014). Geothermal projects on federally managed land⁵⁷ may be subject to an environmental review process under NEPA as many as six times—from agency land-use

planning through construction of a power plant and associated transmission infrastructure (Figure 2-19) (Young et al. 2014).

Data from the exploration and resource-confirmation phases of a geothermal project determine whether and how to proceed with developing the project. Under existing processes, each phase in the geothermal development process may require a subsequent NEPA review. As shown in Figure 2-19, geothermal resource management may require a separate NEPA review at the land-use planning (1) and leasing (2) phases before federal agencies consider lands for leasing, followed by another NEPA review for exploration (3) and resource confirmation (4), a NEPA review for development of a wellfield (5), and an Environmental Impact Statement for the power plant and transmission lines (6). Some geothermal developers have attempted to conduct NEPA reviews that evaluate these multiple project phases in one step, but such approaches have had limited success (Young et al. 2019).⁵⁸

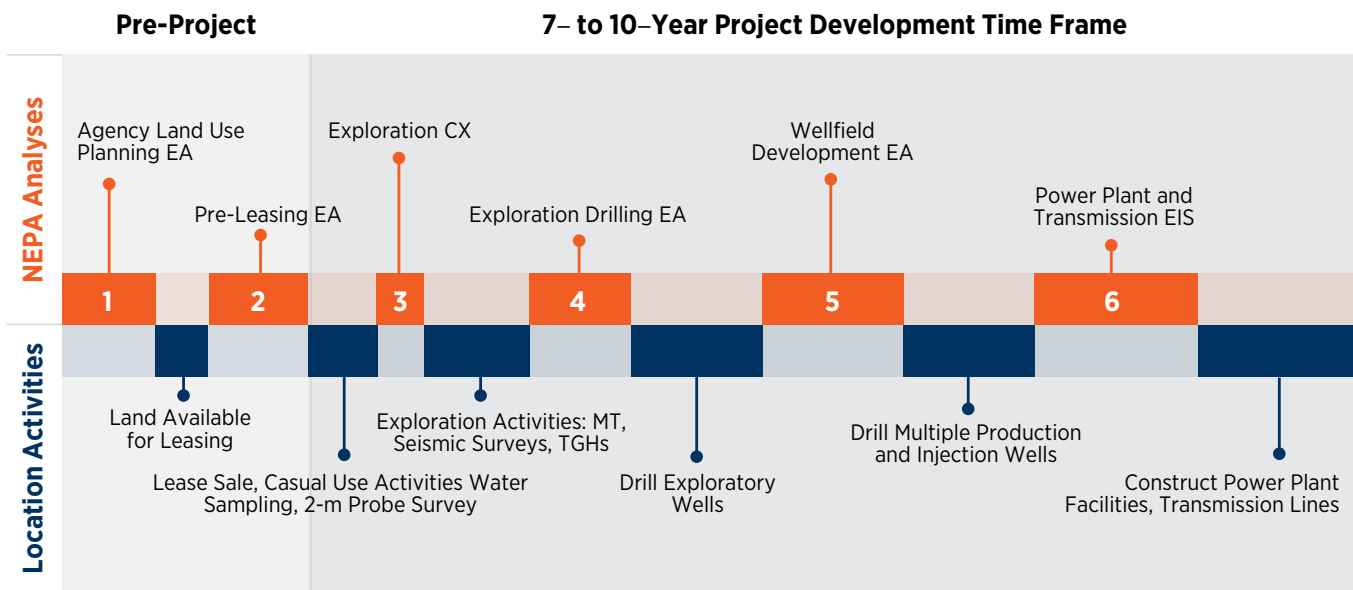


Figure 2-19. Example timeline of a geothermal project on federal lands, illustrating that a single location could trigger National Environmental Policy Act analysis six separate times

Source: Young et al. 2014

Figure Note: EA = Environmental Assessment, EIA = Environmental Impact Statement, CX = categorical exclusion, MT = magnetotelluric, and TGH = temperature-gradient hole.

⁵⁷ The BLM serves as the lead agency for most geothermal projects on leased federal land and has the authority to approve most operations on leased federal lands (e.g., exploration, drilling, power plant, and transmission line construction).

⁵⁸ Combined NEPA reviews are more time-intensive and increase upfront risks and costs for a developer. Combined NEPA reviews that are based on incomplete or inadequate resource information (pre-confirmation drilling) require the proposal and inclusion of a wide array of potential sites and development permutations as part of the NEPA review. These potential sites are required in order for a developer to secure back-up development locations to adequately reduce the upfront risks. In addition to the increased risks and costs for a developer, these requirements generate more work for the corresponding federal agencies conducting the NEPA review, because agencies need to evaluate longer documents and multiple sites—many of which will ultimately not be used for development.

Environmental reviews required under NEPA are essential to ensure protections for federally managed lands and overall environmental quality. However, as noted, those reviews can contribute to development delays, including for geothermal projects. The *GeoVision* analysis explored pathways to complete environmental reviews for geothermal projects under reduced timelines. Depending on the nature and complexity of the activity under consideration, there are several levels of NEPA review that may be used, including a categorical exclusion,⁵⁹ an Environmental Assessment, or an Environmental Impact Statement.⁶⁰ Each of these pathways to NEPA compliance has different requirements.

Existing BLM regulations⁶¹ include one categorical exclusion specific to geothermal exploration, stipulating that exploration activities may not cause any new surface disturbance (e.g., access road, drill pad) or touch the geothermal resource (BLM 2016, Department of Interior 516 DM 11.9(B)(6)). Although the review period for the existing BLM geothermal categorical exclusion only takes a couple of months, the scope of drilling permitted under the categorical exclusion does not provide the data required to confirm the geothermal resource. Because additional steps and NEPA analyses are required, confirming the resource is more costly and risky. The delay and need for additional steps can result in a 5–7-year period (rather than a 1–3-year period) for a permit applicant to demonstrate a bankable geothermal development (Beckers et al. 2018, Young et al. 2019).⁶²

2.4.3.2 Non-Technical Barriers: Non-Electric Sector

Non-technical barriers to deployment of geothermal resources for the non-electric sector relate primarily to soft costs such as market barriers and consumer adoption. Barriers include a lack of awareness and

understanding by the public, utilities, regulators, and policymakers, and a shortage of professionals skilled in the geothermal non-electric technologies. Development in the non-electric sector can also be hindered by market mechanisms that do not adequately value the benefits offered by GHP systems.

Geothermal District Heating

The *GeoVision* analysis of simulation outputs and geothermal district-heating case studies (Fleischmann 2007, Thorsteinsson and Tester 2010, Snyder et al. 2017) identified several key barriers to widespread district-heating deployment in the United States. Policy and market barriers to geothermal district heating include competition from alternative heating sources, especially natural gas; a lack of federal or state incentives such as subsidies or tax credits used in other countries or for other renewable energy technologies; and a shortage of geothermal professionals, consultants, and businesses along with a general aging of the existing geothermal workforce.

Geothermal Heat Pumps

Major barriers to rapid consumer adoption of GHP technologies include high initial upfront costs, poor public awareness and confidence, historically lukewarm government support, lack of appropriate market resale valuation, and slow development of new technologies to improve GHP system cost and performance (New York State Energy Research and Development Authority 2017). Although low fossil fuel prices have reduced the effect of energy savings, barriers to GHP deployment are exacerbated because the market has few mechanisms to assign value to other environmental and social benefits of GHP systems.

⁵⁹ As discussed in Section 3.2.1.2, the *GeoVision* analysis included an expansion of categorically excluded activities as one of many pathways for an Improved Regulatory Timeline scenario. A categorical exclusion can be applied when a project's activities fit within a list of actions that an agency has determined do not significantly affect the quality of the human environment. A categorical exclusion is one option that complies with the National Environmental Policy Act, which is required for projects that are on federal lands, supported with federal funds, or otherwise include a major federal action. Categorical exclusions exist for some oil and gas and geothermal development categories, covering geophysical and exploration activities, including the drilling of temperature gradient holes with no new surface disturbance.

⁶⁰ Categorical exclusion: 40 CFR §1508.4; Environmental Assessment: 40 CFR §1508.9; Environmental Impact Statement: NEPA Sec. 102 [42 USC § 4332] and 40 CFR §1508.11.

⁶¹ Categorical exclusions can be created either via legislation or through agency regulations within existing statutory authority (e.g., within BLM's authority).

⁶² Bankable describes a bank's willingness to finance a geothermal project, based on demonstrable and sufficient collateral, future cashflow, and probability of success to be acceptable to institutional lenders for financing. Sufficient data—often as many as three wells drilled into the reservoir capable of producing at least 50% of the expected enthalpy—must be provided to allow for financing (Beckers et al. 2018).



CHAPTER THREE

GeoVision Analysis: Models and Scenarios

Pressure-control equipment on a geothermal well flow test.

Photo credit: Piyush Bakane

3 *GeoVision* Analysis: Models and Scenarios

The *GeoVision* analysis used detailed, quantitative modeling to assess the potential for geothermal deployment under varied scenarios that consider a range of technologies, market conditions, and barriers. Chapter 3 summarizes the modeling analytics and approach used in the analysis. Section 3.1 introduces the modeling platforms and Section 3.2 discusses the various scenarios.

3.1 *GeoVision* Models

The *GeoVision* analysis used comprehensive research, modeling, and data analysis to quantify electric- and non-electric-sector deployment levels within credible and realistic market constraints. A range of impact models was then used to quantify the economic and workforce benefit to the geothermal industry and environmental impacts for the United States under the projected deployment levels (Chapter 4). Modeling platforms and assumptions used in the *GeoVision* analysis are introduced here and described further in Appendix C and Augustine et al. 2019. Not all assumptions and data are included in this chapter or Appendix C; detailed descriptions of the modeling tools, inputs, methodologies, and scenarios that form the quantitative basis for the *GeoVision* analysis are provided in Lowry et al. 2017, Doughty et al. 2018, Augustine et al. 2019, Liu et al. 2019, McCabe et al. 2019, and Young et al. 2019.

3.1.1 Geothermal Electricity Technology Evaluation Model

The *GeoVision* analysis used the U.S. Department of Energy’s (DOE’s) Geothermal Electricity Technology Evaluation Model (GETEM)⁶³ to estimate the cost of developing geothermal resources for electric-power

generation under various technology scenarios. GETEM is a Microsoft Excel-based model that estimates the overall capital costs, operations and maintenance (O&M) costs, and levelized cost of electricity to develop hydrothermal and enhanced geothermal systems (EGS) projects. GETEM does this using a bottom-up, deterministic model that calculates individual component costs by project phase, such as exploration, wellfield development, and power-plant construction. GETEM is based on user-defined cost inputs, embedded cost and system performance correlations, and cost indices to adjust for the year the project is developed.

GETEM was used to estimate the overnight capital⁶⁴ and O&M costs for the hydrothermal and EGS resources described in Section 2.1 on a site-by-site basis. Inputs to GETEM for the *GeoVision* analysis included the resource type—either conventional hydrothermal or EGS—and a power-plant technology configuration based on resource parameters such as temperature,



Steam pipelines at the Bottle Rock geothermal power plant (The Geysers in California). Photo credit: Betsy Phillips

⁶³ The GETEM model is available on the DOE website at <https://energy.gov/eere/geothermal/geothermal-electricity-technology-evaluation-model>.

⁶⁴ Overnight capital costs are defined as the capital expenditure required to achieve commercial operation of a power plant, excluding the construction period and the financing and interconnection costs.

depth, and project type. The results were used to develop geothermal resource supply curves—a plot of technology resource potential versus the cost to develop the applicable resource. This curve shows how much of a resource is available as well as the cost associated with constructing and using a given power-plant technology to harness the resource for electricity generation. The approach and methodology closely followed the one described in Augustine 2011. Supply curves resulting from GETEM were then entered into the Regional Energy Deployment System (ReEDS) (Section 3.1.2) to support comparisons and capacity-deployment decisions among alternative power-generation technologies.

3.1.2 The Regional Energy Deployment System Model

Developed by DOE’s National Renewable Energy Laboratory (NREL), the ReEDS⁶⁵ model considers the many electricity generation, storage, and transmission options across the contiguous United States. The model identifies the cost-optimal mix of technologies that meets regional electric-power demand based on grid-reliability requirements, technology-resource constraints, and policy constraints. As a capacity-expansion and dispatch model, ReEDS uses system-wide, least-cost optimization to estimate the type and location of future generation and transmission capacity (Eurek et al. 2016). ReEDS has been used to model capacity expansion for a number of other DOE Vision analyses, including the *Wind Vision*,⁶⁶ *Hydropower Vision*,⁶⁷ and *SunShot Vision*,⁶⁸ as well as the *Renewable Electricity Futures* study.⁶⁹

For the *GeoVision* analysis, the geothermal-resource supply curves calculated in GETEM (Section 3.1.1) were inputs to the ReEDS model. In addition to the resource supply curves, ReEDS used scenario-based metrics identified by the *GeoVision* analysis task forces, such

as project financing and construction timelines. The ReEDS and GETEM model interface and workflow are elaborated in Augustine et al. 2019. Outputs from ReEDS included the amount and location of production capacity and annual generation from each potential electricity-generation technology, including geothermal technologies, as well as storage capacity expansion, transmission capacity expansion, total electric-sector costs, electricity price, fuel demand and prices, water withdrawals and consumption, and carbon dioxide emissions.



Springtime at Surprise Valley Hot Spring in California.
Photo credit: Joe LaFleur

Because ReEDS is a system-wide least-cost optimization model, it does not consider revenue impacts for individual project developers, utilities, or other industry participants. The model also does not resolve some other factors that may influence power-system economics, including the following:

- Constraints associated with the supply chain and manufacturing sector are not included internally in ReEDS. All technologies are assumed to be available up to their technical resource potential.

⁶⁵ The ReEDS model is available on NREL’s website at <https://www.nrel.gov/analysis/reeds/>.

⁶⁶ <https://www.energy.gov/eere/wind/wind-vision>

⁶⁷ <https://www.energy.gov/eere/water/new-vision-united-states-hydropower>

⁶⁸ <https://www.energy.gov/eere/solar/sunshot-vision-study>

⁶⁹ <https://www.nrel.gov/analysis/re-futures.html>

- Technology cost reductions from manufacturing economies of scale and “learning by doing” are not calculated in the model internally. These market behaviors are defined as inputs that do not depend on the capacity deployed by the model.
- With the exception of projecting future natural-gas fuel costs, foresight is not considered explicitly in ReEDS. The model makes investment decisions based on the conditions it observes at a given point in time, without considering how those conditions may change in the future.
- ReEDS is deterministic and has limited considerations for risk and uncertainty, so it cannot study variability in energy availability from year to year. As such, the model is restricted to projections of average system behavior.
- As an electric-sector-only model, ReEDS does not directly include fuel infrastructure, challenges of land competition associated with fossil-fuel extraction and delivery, or challenges of water competition associated with agricultural or other use.



Fly Geyser in northern Washoe County, Nevada.
Photo credit: Harmony Ann Warren

3.1.3 Distributed Geothermal Market Demand Model

As noted in Sections 3.1.1 and 3.1.2, the *GeoVision* analysis used GETEM to determine geothermal development costs and resource supply curves in the electric sector and ReEDS to determine geothermal electric-power deployment potential. To evaluate the non-electric heating and cooling sector, DOE developed a dedicated modeling tool called the Distributed Geothermal Market Demand (dGeo) model (Gleason et al. 2017, McCabe et al. 2019).

The dGeo model simulates the potential for deployment of distributed geothermal-energy resources in the residential and commercial sectors of the contiguous United States for two technologies: geothermal heat pumps (GHPs) and geothermal direct-use applications for district heating. To quantify these opportunities, dGeo leverages a high-resolution geospatial database and robust modeling framework whose design is based on and consistent with other Distributed Generation Market Demand models (Sigrin et al. 2016), such as NREL’s dSolar model.⁷⁰

dGeo is a long-term scenario-modeling tool. The model has the capability to simulate the technical, economic, and market potential and the technology deployment of GHP and geothermal district-heating applications through 2050 under user-defined input scenarios. Scenarios in dGeo consider changes in costs, performance, and financing; costs of heating and cooling alternatives; and regional heating and cooling energy demand and the potential of geothermal resources to meet that demand. In addition to determining the economic resource potential for geothermal district heating and GHP deployment, the dGeo model also has the capability to identify the extent and speed with which the market can adopt

⁷⁰ Information about the NREL dSolar module is available on the NREL website: <https://www.nrel.gov/analysis/dgen/model-applications.html>.

those resources based on consumer behavior.⁷¹ The dGeo market-potential assessment considers regulatory and policy limitations and regional competition with other energy sources.

Figure 3-1 illustrates the various levels of potential that can apply to all types of geothermal resources. *Resource* potential is the total geothermal energy available, based solely on physical characteristics such as volume and heat content. *Technical* potential is the portion of the overall resource that can technically be accessed, considering limitations such as land access, physical access to the reservoir, and equipment efficiency. *Economic* potential is that portion of technical potential that is cost effective to recover based on technology costs and anticipated revenues. *Market* potential indicates how much of and how quickly the resources could actually be adopted and deployed from the economic potential, given market conditions such as regulatory environment, capital availability and investor interest, consumer demand, and energy competition.

The *GeoVision* analysis focused on technology applications with proven track records and sufficient examples from which to develop model parameters. For GHPs, heating and cooling applications were considered. However, only geothermal district heating was considered for direct-use applications; geothermal district-cooling systems were omitted from the analysis given the experimental nature of the technology. A literature review indicated that the technology to support district-cooling systems may exist, but few examples (if any) indicate use of a geothermal resource to provide cooling to a network of buildings. The *GeoVision* analysis included assessment of market potential for GHP technologies. Doing the same for geothermal district-heating applications would require determining the consumer adoption behavior of large groups and communities, which was outside the scope of the *GeoVision* analysis. As such, the analysis for geothermal district-heating applications considered only economic potential.

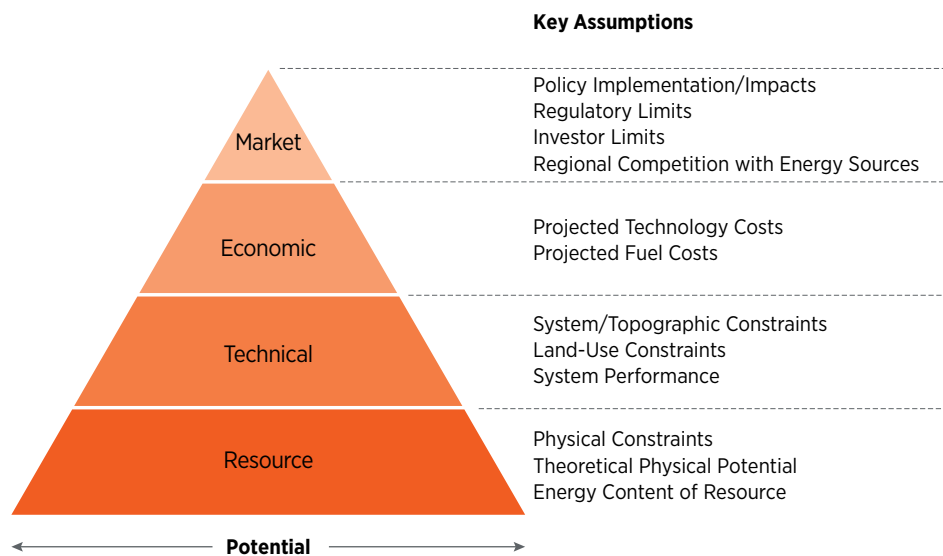


Figure 3-1. Levels of geothermal potential in the dGeo model

Figure Notes: For geothermal, **resource potential** is the total projected heat resources, limited only by physical/thermodynamic factors. **Technical potential** is the subset of total resources that will be accessible given land-access restrictions, geographical restrictions, and the performance limits of the installed technologies. **Economic potential** is that amount of resources that is cost effective to develop given technology and development cost projections. **Market potential** includes factors such as consumer demand, regulatory and policy restrictions, investment availability, and competition.

⁷¹ Whereas *economic* potential considers the portion of resource that is economically viable, the *market* potential considers the portion that is likely to be deployed, given the reaction of consumers in the market to economic factors. To determine this market and deployment potential, dGeo first relies on a series of empirically derived curves that relate the economic attractiveness of technology adoption and maximum market share for each modeled consumer entity (e.g., an organization or group). Maximum market share is the portion of the market that will eventually adopt the technology given its economic attractiveness. dGeo simulates deployment using the “diffusion of innovations” framework, which establishes how, why, and at what rate technology is spread. Under this framework, technology deployment initially follows slow growth, accelerates as mass-market uptake begins, and then decelerates as the market for the technology reaches saturation.

3.2 GeoVision Scenarios

The *GeoVision* analysis included a range of scenarios to evaluate geothermal deployment potential and the impacts that would result from developing and implementing new geothermal technologies under various market conditions. The subsequent sections summarize the scenarios but do not contain the full body of analysis. The inputs and assumptions are detailed in Doughty et al. 2018, Augustine et al. 2019, McCabe et al. 2019, and Liu et al. 2019.

3.2.1 Electricity Sector Scenarios

Three primary scenarios were modeled in the *GeoVision* analysis to explore geothermal deployment potentials within the electric sector: 1) Business-as-Usual (BAU), 2) Improved Regulatory Timeline (IRT), and 3) Technology Improvement (TI). Table 3-1 summarizes the scenarios and their key assumptions with respect to capital and O&M costs, construction times, financing, and undiscovered hydrothermal resource discovery rates. The scenarios are progressive and cumulative.

Scenario	Business-as-Usual	Improved Regulatory Timeline ⁷²	Technology Improvement
Description	Reflects current industry trends	Streamlined permitting increases the amount of exploration, decreases project timelines, increases resource discovery rate	IRT scenario + access and technology improvements: Advances in drilling, exploration, and EGS reservoir development reduce costs and risks
Capital + O&M Costs	BAU	BAU	Hydrothermal: some reductions EGS: large reductions
Construction Time (years)⁷³	Hydrothermal: 8 EGS: 10	Hydrothermal: 4 EGS: 5	Hydrothermal: 4 EGS: 5
Financing⁷⁴	BAU	BAU	ReEDS Standard WACC (8%)
Hydrothermal Discovery Rate⁷⁵	1% of undiscovered resource/year	3% of undiscovered resource/year	3% of undiscovered resource/year

Table 3-1. The *GeoVision* Analysis Electric-Sector Scenarios

Table Notes: The primary scenarios for the electric sector include: (a) the Business-as-Usual scenario, which reflects industry status and projected trends at the time of the *GeoVision* analysis; (b) the Improved Regulatory Timeline scenario, which includes assumptions of various regulatory and permitting efficiency improvements that result in reduced development timelines; and (c) the Technology Improvement scenario, which includes the streamlined permitting improvements of the Improved Regulatory Timeline scenario with additional advances in technologies for exploration, drilling, and reservoir stimulation that decrease development costs and risks. WACC refers to “weighted-average cost of capital” and represents the financing rates that projects are able to achieve (see Augustine et al. 2019).

⁷² The IRT scenario assumed shortened development timelines aided by streamlined permitting processes; time is the principal variable adjusted in the model. Potential regulatory-related scenarios for these shortened timeframes include centralized permitting offices and a categorical exclusion that would allow drilling and testing of confirmation wells—consistent with the general parameters established for oil and gas in section 390 of the 2005 Energy Policy Act of 2005 (EPAct 2005) and as proposed for the geothermal industry in section 3012 of S. 1460, the Energy and Natural Resources Act of 2017 (115th Congress)—to prove out a reservoir and allow for project financing for the remainder of the project. The details of such streamlined processes were not explored for this scenario, but a study by the Bureau of Land Management was underway at the time of this report to explore this concept in more detail.

⁷³ The construction timeline is the time from pre-exploration to when the project starts providing electricity to the grid. ReEDS implementation starts the clock on costs and time with the pre-drilling exploration phase (see Table 3-2). The basis for construction timelines used in the *GeoVision* analysis is detailed in Augustine et al. 2019 and Young et al. 2019.

⁷⁴ In the BAU and IRT scenarios, financing (weighted-average cost of capital) for geothermal is about 6% higher than other power-generation technologies (e.g., wind, solar) in ReEDS to reflect high risks and equity financing requirements at the beginning of geothermal projects. Technology improvements in the TI scenario are assumed to increase success rates and decrease development risk such that developers can obtain financing at the same weighted-average cost of capital available to other generation technologies (the ReEDS Standard Weighted Average Cost of Capital, 8%).

⁷⁵ The increase in discovery rate for undiscovered geothermal resources is based on multiple industry surveys performed as part of the *GeoVision* analysis and considers a decrease in time required to obtain exploration permits. In the IRT scenario, reduced time for permitting greatly increases the amount of exploration that is performed, which ultimately results in more discoveries (Augustine et al. 2019). Discovery rates were conservatively held constant at 3% for the TI scenario because it was not possible to quantify an improvement based on yet-unforeseen technology improvements. Instead, technology improvements in the TI scenario were translated conservatively through to the model in the form of lower technology costs, lowered project risk, and the more competitive weighted-average cost of capital available to other technologies (the ReEDS Standard Weighted Average Cost of Capital, 8%).

The three scenarios were used as inputs for the ReEDS capacity deployment model (Section 3.1.2). Other electricity-generation technologies—including fossil fuel, wind, and solar—were modeled using inputs from the Mid-case scenario of the 2016 Annual Technology Baseline (Cole et al. 2016a).⁷⁶ Future electricity demand also comes from the Annual Technology Baseline, which uses the 2016 Annual Energy Outlook projections from the U.S. Energy Information Administration (Energy Information Administration 2016).

Table 3-2 summarizes the total amount of geothermal resources available for development as new electricity generation under each of the three *GeoVision* scenarios (refer to Section 2.1 for a description of resource types). The values of resource potential used in ReEDS are smaller than the total resource values in Section 2.1 for several reasons. Resources in Hawaii and Alaska are not included because ReEDS only models the contiguous United States (see Text Box 2-1). In addition, resource potential in ReEDS excludes areas where geothermal development is legally prohibited, including National Parks and Monuments. The *GeoVision* analysis also identified environmentally sensitive areas such as Wild and Scenic Rivers and National Wildlife Refuges and classified those as areas where geothermal development would be unlikely and/or would face significant barriers. Environmentally sensitive areas were screened and removed from the resource supply curves that provide the basis for the *GeoVision* analysis scenario modeling. The specific barriers included in the available resource assumption vary by scenario, with the TI scenario assuming fewer barriers and, hence, more land areas and accessible resources available for development (Young et al. 2019). Sections 3.2.1.1–3.2.1.3 summarize the available resource potential assumptions and additional barriers. More detail is available in Young et al. 2019 and Augustine et al. 2019.

<i>GeoVision</i> Scenario	Identified Hydrothermal MW _e	Undiscovered Hydrothermal MW _e	Near-Field EGS MW _e	Deep EGS MW _e
BAU and IRT	5,078	18,830	1,382	3,375,275
TI	5,128	23,038	1,443	4,248,879

Table 3-2. Geothermal Resources Available for Development for Electricity Generation (in megawatts-electric, MWe) in the Regional Energy Deployment System Model (ReEDS) under the *GeoVision* Analysis Scenarios

3.2.1.1 Business-as-Usual Scenario

The BAU scenario reflected industry trends and the anticipated future if the industry continues on the same path as 2016 conditions. The *GeoVision* analysis evaluated existing and projected industry capital costs, construction timelines, and project financing. The BAU scenario includes a primary assumption related to the rate of discovery of undiscovered hydrothermal resources. Roughly 75%—about 30,000 megawatts-electric (MW_e)—of the total available conventional hydrothermal resource base is classified as undiscovered (Williams 2008). Because of this, the full resource calculated in the *GeoVision* analysis supply curves is not available for immediate development or deployment. The *GeoVision* analysis included extensive examination and discussion with industry experts to conclude that, under the BAU scenario, 1% (about 200 MW_e) of total undiscovered resources would be found and available for development each year; this is the rate of discovery used in the BAU scenario.

3.2.1.2 Improved Regulatory Timeline Scenario

The IRT scenario was based on the *GeoVision* barriers analysis (Young et al. 2019), which considered a number of pathways and potential combinations of approaches to streamline and reduce project development timelines. Analyzed options are explained in Section 2.4.3.1 and included 1) a geothermal categorical exclusion specific to resource confirmation activities;

⁷⁶ The Mid-case scenario is a reference scenario that reflects “business-as-usual” conditions applied to the bulk power system model in ReEDS. This scenario is described in detail in the 2016 NREL Standard Scenarios report (Cole et al. 2016b). The Mid-case scenario assumes 1) the 2016 reference cases from the Energy Information Administration’s Annual Energy Outlook for electricity demand growth and natural gas prices, 2) mid-case projections for electricity-generation technology costs from the 2016 Annual Technology Baseline, 3) a reference case for existing fleet retirements based on the ABB Velocity Suite database, 4) existing policies as of April 1, 2016 (with the exception of the Clean Power Plan, which is removed), 5) no system feedback due to changes in the Earth’s climate, and 6) default resource constraints (Cole et al. 2016a). The Mid-case scenario assumptions were used as inputs in ReEDS for the *GeoVision* analysis for all technologies except geothermal, which used the *GeoVision* analysis inputs for the BAU, IRT, and TI scenarios as described herein.

2) a federal coordinating permit office with dedicated geothermal experts⁷⁷; 3) expanded use of pre-leasing Environmental Assessment to include analysis of a limited amount of surface-disturbing activities; and 4) an updated Programmatic Environmental Impact Statement. Activities assumed as part of the *GeoVision* analysis IRT scenario are limited to the activities elaborated in Young et al. 2019.

The IRT scenario is consistent with the March 21, 2017, Executive Order 13783, which discusses the national interest in terms of, “...promoting clean and safe development of our Nation’s vast energy resources, while at the same time avoiding regulatory burdens that unnecessarily encumber energy production, constrain economic growth, and prevent job creation...” The Order further mandates, “...immediate review of all agency actions that potentially burden the safe, efficient development of domestic energy resources.” The *GeoVision* analysis IRT scenario included evaluation of the effects of potential reforms in furtherance of Executive Order 13783, as assessed by DOE and the U.S. Department of Agriculture.

In response to this Executive Order, DOE issued its report titled, “Final Report on Regulatory Review Under Executive Order 13783” (DOE 2017). The report includes recommendations for domestic energy development and use, including a review of DOE National Environmental Policy Act policies to determine whether DOE should grant more categorical exclusions, assess whether DOE should adopt categorical exclusions already approved by other federal agencies, and foster interagency collaboration, such as working with the Bureau of Land Management to consider categorical exclusions for geothermal energy on federal lands.

Also in response to Executive Order 13783, the U.S. Department of Agriculture reviewed more than 70 U.S. Forest Service actions, culminating in recommendations for parts of 15 existing agency actions that could be revised or rescinded to alleviate or eliminate burdens on the development or use of domestic energy

The Improved Regulatory Timeline scenario in the *GeoVision* analysis models the impacts of reduced development timelines resulting from regulatory streamlining, but does not assume or create new policies that have not otherwise been introduced.

resources. As part of the review process, the U.S. Department of Agriculture identified three top priorities that would show early and measurable results. Two of the top three priorities concerned reform relevant to geothermal leasing and permitting (U.S. Department of Agriculture 2017):

- **Revise U.S. Department of Agriculture/U.S. Department of the Interior Memorandum of Understanding.**

The Forest Service has seen increased activity in Expressions of Interest for geothermal development on National Forest System lands. As of 2017, 118,000 acres were leased on National Forest System lands for geothermal energy production. The Forest Service recommended the revision of the U.S. Department of Agriculture and U.S. Department of the Interior’s “Memorandum of Understanding Implementing Section 225 of the Energy Policy Act of 2005 Regarding Geothermal Leasing and Permitting.” The revision will clarify the roles and responsibilities of the two agencies to allow for increased geothermal development.

- **Require consideration of geothermal leasing and development in national forests with high geothermal resource potential.**

The Forest Service recommended revision of Forest Service Handbook Section 1909.12 Chapter 20 Section 23.23i to include requirements from Sec. 222.4.d.1 of the 2005 Energy Policy Act (EPA 2005), which requires forest plans with high

⁷⁷ Centralized and/or coordinating permit offices exist within the Bureau of Land Management for both oil and gas and renewable energy projects. In 2005, under Section 365 of EAct 2005, Congress established a Federal Permit Streamlining Pilot Project, which designated seven Bureau of Land Management field offices in Colorado, Montana, New Mexico, Utah, and Wyoming to serve as offices to coordinate and process oil and gas authorizations on federal land. The offices coordinate approvals between agencies within the Department of the Interior, Department of Agriculture, U.S. Army Corps of Engineers, and the U.S. Environmental Protection Agency (Levine et al. 2013). In addition, in 2009, the Bureau of Land Management established the National Renewable Energy Coordination Office, which included program leads for wind, solar, and geothermal. Soon after, regional Renewable Energy Coordination Offices were created in Arizona, California, Nevada, and Wyoming, focused on solar and wind permitting and coordination. At the national level, the Bureau of Land Management geothermal program is a part of the Renewable Energy Coordination Office, whereas at the regional level, these offices are staffed predominately with realty specialists (as opposed to geologists or subsurface specialists), creating a disconnect in skill sets necessary to process geothermal permit and regulatory approvals. As a result, state geothermal programs do not interact with the regional Renewable Energy Coordination Offices at all, whereas other state geothermal programs may only report geothermal project status during scheduled Renewable Energy Coordination Office teleconferences.

geothermal resource potential to be considered for geothermal leasing and development.

The IRT scenario considers the impact that reduced regulatory burdens and streamlined regulations mandated by Executive Order 13783 could have on the geothermal industry. For the *GeoVision* analysis, the variables adjusted within the deployment models were limited to construction time and resource exploration and discovery rates. The analysis determined the extent to which the time and discovery rate variables could plausibly be impacted under different improvement scenarios (Young et al. 2019). The IRT scenario represented one of several permutations of regulatory streamlining and combined improvements that, if successful, could result in up to a 4-year reduction in permitting timelines for hydrothermal projects and a 5-year reduction for EGS projects. Reduced permitting timelines can reduce construction timelines and improve project financing costs as modeled in the *GeoVision* analysis. Results indicate that more and easier exploration under the IRT scenario would increase discovery rates for undiscovered hydrothermal resources from 1% to 3% per year over the BAU scenario (Young et al. 2019).

3.2.1.3 Technology Improvement Scenario

The TI scenario primarily evaluated the impacts of aggressive technology advances and cost reductions on the potential for geothermal deployment. This scenario assumed that the construction of large utility-scale power plants continues to be the predominant goal of project developers and that geothermal providers have advanced technology breakthroughs from a confluence of technology improvements. Many of these technology improvements will require early-stage research and development (R&D) and have been included in the *GeoVision* Roadmap as actions that can help achieve the improved costs and performance assumed in the TI scenario. The TI scenario assumed technology improvements in the areas of resource exploration, drilling, and reservoir creation. The TI scenario technology assumptions are summarized in Table 3-3 and detailed in Augustine et al. 2019.

The TI scenario assumed technology improvements in exploration techniques and technologies that do not directly reduce pre-drilling exploration costs but do increase the ability to successfully identify and target geothermal resources. This results in higher drilling and project success rates for developments that move beyond the pre-drilling phase. Better targeting also translates into increased drilling success rates (fewer dry holes), reduced overall project risk, and decreased financing costs. Advances in drilling technology lead to significant reductions in drilling and well completion costs. The TI scenario also assumed technology improvements in reservoir stimulation that result in EGS reservoirs with performance characteristics—such as flow rate and well productivity⁷⁸—that are similar to conventional hydrothermal resources.



Arrival of condensers at the Blue Mountain Faulkner 1 geothermal power plant in Nevada. Photo credit: John Casteel

Improvements described in Table 3-3 are incorporated into the *GeoVision* analysis as reductions in capital and O&M costs. Figure 3-2 shows the reductions in overnight capital costs for a representative hydrothermal flash plant and EGS binary plant that result from the TI scenario technology-improvement assumptions. The charts illustrate the cost reductions from technology improvements in each area independently and combined (full TI scenario), compared to costs under the BAU scenario. For both plants, the sum of cost reductions from individual areas is larger than the total impact from implementing them simultaneously. This is because the geothermal cost-model inputs are highly interrelated. For example, project drilling costs can be decreased by technology improvements that

⁷⁸ Volumetric well flow rate refers to the volume of fluid produced per unit time, typically reported as gallons/minute or liters/second. Well mass flow rate refers to the mass of fluid produced per unit time, typically reported as 1,000 pounds (mass) per hour (thousands of pounds mass per hour) or kilograms per second. Productivity index refers to ratio of total liquid surface flow rate to the pressure drawdown (differential between the reservoir pressure and wellbore pressure) at the midpoint of a producing interval in a well, typically reported as gallons per minute per pounds per square inch, or gpm/psi, thousands of pounds mass per hour, per pounds per square inch, or kg/s/bar.

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 project. Improvements in drilling technologies that increase the drilling success rate and/or lower drilling costs have the largest impact on capital costs

for conventional hydrothermal plants. For EGS, the increase in well flow rate and productivity leads to the largest reduction in overnight capital costs. Appendix C provides more detailed supply curves and additional information about cost assumptions.

GETEM Input		Business-as-Usual		Technology Improvement	
		Hydrothermal	EGS	Hydrothermal	EGS
RESOURCE EXPLORATION	<i>Exploration—Pre-Drilling Costs (\$/project)</i>	\$600K–\$1.2M	\$250K	Same as BAU	
	<i>Exploration—Drilling Costs (\$/project)</i>	\$3.3M–\$5.4M	\$1.5M–\$5M	Two-thirds of BAU	
	<i>Full-Sized Confirmation Well Costs⁷⁹</i>	Base + 20%	Base + 50%	Ideal + 0% (no premium)	
	<i>Full-Sized Confirmation Well Success Rate</i>	50%	50%	75% (with stimulation)	
	<i>Number of Full-Sized Confirmation Wells</i>	3	9	3	
DRILLING	<i>Drilling Success Rate⁸⁰</i>	75%		90%	
	<i>Drilling Costs⁸¹</i>	Base		Ideal	
RESERVOIR CREATION	<i>Stimulate Wells?</i>	No	Yes	Yes	
	<i>Well Flow Rate (flow rate per production well)</i>	Flash: 80 kg/s Binary: 110 kg/s	40 kg/s	Flash: 80 kg/s Binary: 110 kg/s	
	<i>Well Productivity</i>	4.6 kg/s/bar (5.8 gpm/psi)	0.46 kg/s/bar (0.58 gpm/psi)	4.6 kg/s/bar (5.8 gpm/psi)	

Table 3-3. Summary of Technology Improvement Scenario Assumptions

Table Notes: (1) Exploration pre-drilling activities typically involve geological, geophysical, and geochemical surveys. These surveys might include, but are not limited to, activities such as geological and structural mapping, remote-sensing data analysis, geophysical assessments of resistivity and temperature data, and geochemical surveys of groundwater and surface water and rock alteration. (2) The TI scenario assumes that the construction of large utility-scale power plants continues to be the predominant goal of project developers and that geothermal providers have advanced technology breakthroughs from a confluence of technology improvements. These improvements include the availability of big data to optimize exploration and drilling, advanced exploration drilling techniques such as micro-hole drilling, reductions in costs and improvements in the success rate of drilling overall, and the development of EGS techniques such as multistage stimulation of deviated wells that increase the productivity and longevity of EGS reservoirs. (3) The TI scenario assumes the BAU values for all other GETEM inputs. The GeoVision analysis used identical GETEM inputs for the geofluid gathering system and pumping, O&M, and power plant for both the BAU and TI scenarios. Values for these inputs can be found in Augustine et al. 2019. (4) kg/s = kilograms per second; kg/s/bar = kilograms per second per bar; gpm/psi = gallons per minute per pounds per square inch.

⁷⁹ GETEM inputs were structured assuming that the costs of confirmation wells are more expensive than standard production wells drilled during the field-development phase. Costs of standard production wells are based on the drilling cost curves considered as the basis for the *GeoVision* analysis and as elaborated in Lowry et al. 2017. Costs of full-size confirmation wells consider the standard production well cost plus the indicated premium as a percentage of the standard well cost. Lowry et al. 2017 and Augustine et al. 2019 provide a complete description of geothermal well-construction sizes, their cost-benefit relationships, and the manner in which costs are integrated within GETEM and the *GeoVision* analysis.

⁸⁰ Drilling success rates are for full-size production and injection wells. Success rates are assumed to be the same for brownfield and greenfield sites.

⁸¹ Drilling cost curves are taken from Lowry et al. 2017 for ideal and base well cost scenarios.

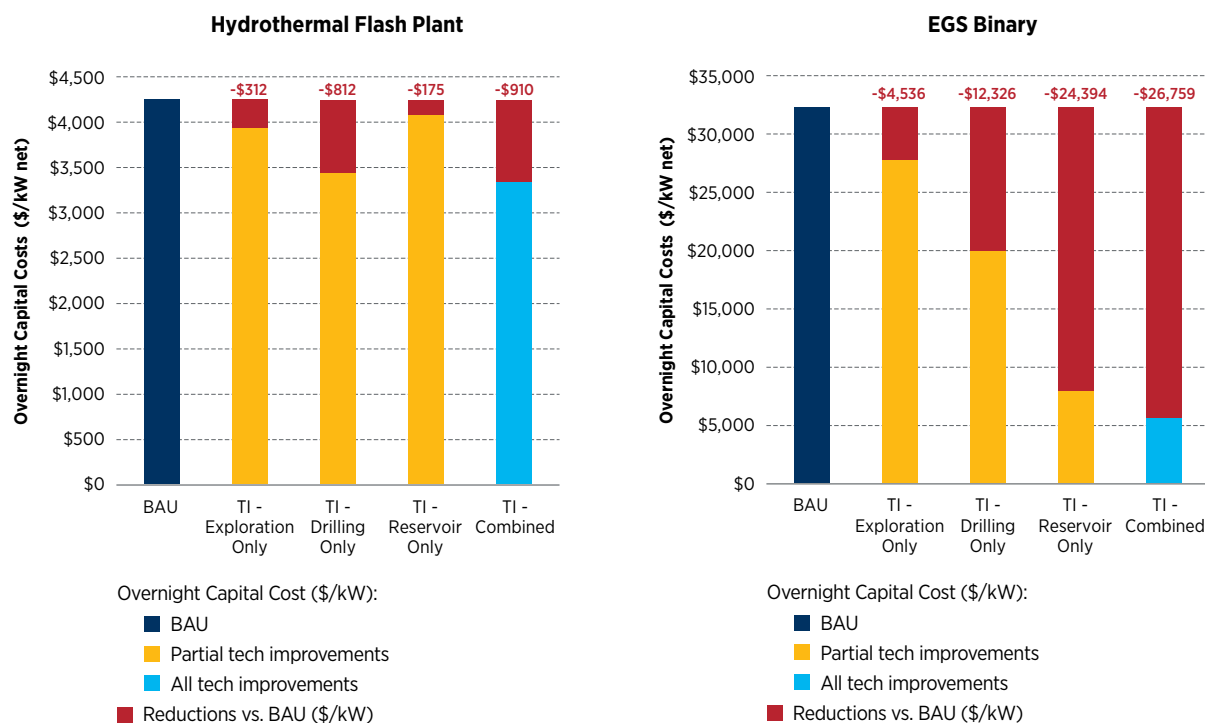


Figure 3-2. Waterfall charts illustrating reductions in overnight capital costs for hydrothermal flash plant (left) and enhanced geothermal system binary plant (right) projects from the Technology Improvement scenario assumptions

Figure Note: Hydrothermal plant cost estimates assume a representative 40-MW_e flash plant with a resource temperature of 225°C at a depth of 2,500 m. EGS plant cost estimates assume a representative 25-MW_e binary plant with a resource temperature of 175°C at a depth of 3,000 m.

The TI scenario also assumed that geothermal projects are able to obtain financing at rates similar to other energy-generation technologies—the ReEDS Standard Weighted-Average Cost of Capital (8%) (Table 3-1). By comparison, financing under the BAU and IRT scenarios was equivalent to the ReEDS Standard Weighted-Average Cost of Capital plus a 6% premium to reflect the higher risk and equity financing at the beginning of a project. As noted previously, the *GeoVision* scenarios are cumulative, so the TI scenario also included the regulatory reforms in the IRT scenario.

Technology improvements benefit both hydrothermal and EGS resource development, reducing EGS costs enough to make the technology commercially competitive. Technology and cost improvements were applied gradually in the *GeoVision* modeling so that costs decrease linearly from BAU values in 2015 to TI values in 2030. As explained in Section 2.1.2, EGS technologies are likely to be developed and deployed in stages—expanding from the low-permeability margins of existing conventional hydrothermal sites (in-field

EGS) to previously undeveloped and unexplored deep-EGS sites. To model this transition, the *GeoVision* analysis assumed that EGS reservoir technology improvements were available and first used at near-field EGS sites starting in 2024. Because it will take some time to establish the EGS industry, the growth rate of near-field EGS deployments was artificially limited in the model. This limit started at 50 MW_e per year in 2024 and increased to 200 MW_e per year in 2030 (Augustine et al. 2019). Growth limits were removed starting in 2030, at which time it is assumed that improvements in EGS reservoir technology are available for all EGS resources.

Future Technologies and Resources

DOE has maintained a robust geothermal R&D portfolio since the 1970s. Much of this research has been aimed at developing and deploying improved geothermal exploration techniques that result in better subsurface characterization and reduced risk and costs for exploration. Major areas of focus in the first 30 years of DOE-funded R&D for geothermal exploration

included support for industry exploration and drilling activities, cooperative programs with selected states to help assess geothermal resources, studies of selected hydrothermal systems, geological exploration technique development and analysis, and exploration strategies (DOE 2010a, DOE 2010b).⁸² In addition to the continuing study of improved and innovative exploration technologies, DOE has initiated several EGS research initiatives. These initiatives are intended to address key R&D questions associated with EGS resource characterization, reservoir creation, production sustainability, and operation.⁸³

Accelerated deployment of geothermal resources in the United States could be supported by the development of new technologies and blue-sky concepts that could reduce costs, lower risks, and shorten the time needed to explore and develop all types of geothermal resources.⁸⁴ These types of improvements have occurred in the oil and gas industry, where the development of directional drilling and multistage stimulation revolutionized the use of unconventional oil and gas resources (e.g., Warpinski et al. 2009). The expectation is that the geothermal industry could unlock vast resources through innovative technologies and blue-sky concepts.

A key assumption in the TI scenario was that geothermal developers will have access to technology breakthroughs from a range of improvements in existing technology and the development of innovative technologies (Doughty et al. 2018, Augustine et al. 2019). These breakthroughs would have the effect of improving resource discovery and capture through improved exploration, improved drilling, better well-stimulation success rates, and reduced development costs. The *GeoVision* analysis researched an array of exploration and drilling technologies, including those that demonstrate promise as innovative technologies

that warrant consideration for targeted R&D. The analysis also included a review of blue-sky concepts, or ideas that are out of the mainstream of existing geothermal R&D, with the potential to provide step-change (as opposed to incremental) advancements in geothermal technologies (Doughty et al. 2018). These concepts include supercritical geothermal systems (Text Box 3-1). Some of these technology improvements and concepts are discussed in the *GeoVision* Roadmap (Chapter 5).



A submersible pump on a geothermal production well in western Oregon. Photo credit: Alan Ofsoski

⁸² DOE initiatives that focus on improved exploration technologies include: 1) The Innovative Exploration Techniques initiative, funded by the American Recovery and Reinvestment and Recovery Act of 2009, 2) The Geothermal Play Fairway Program, and 3) the development of methodologies and techniques that improve the ability to discover and characterize undiscovered hydrothermal resources. The projects comprising these three initiatives are discussed in Doughty et al. 2018.

⁸³ DOE initiatives that focus on EGS R&D include: 1) the Frontier Observatory for Research in Geothermal Energy, or FORGE, 2) the EGS Collab project, 3) EGS field-demonstration projects, and 4) DOE subsurface R&D crosscutting research projects. These projects and initiatives are discussed in detail in Doughty et al. 2018.

⁸⁴ Blue-sky research considers areas of R&D in which commercial or other practical applications are not immediately apparent. This research domain is generally recognized as having the potential to realize unanticipated scientific breakthroughs and game-changing industry advancements (Bell 2005).

Text Box 3-1. Supercritical Geothermal Systems

Although not included in the modeling assumptions, the *GeoVision* analysis also evaluated supercritical geothermal systems, which exist wherever subsurface conditions exceed the critical point of water (see Note). In areas of high-heat flow around existing geothermal systems or large volcanic provinces where shallow (<16,000 feet, or about 5 km) magma bodies may exist, supercritical resource conditions can be found at depths that may be cost effective to drill; in fact, supercritical resources can be found everywhere on Earth by drilling deep enough. Based on national-scale assessments of temperature with depth (Blackwell et al. 2011), most areas in the United States would require drilling to depths beyond 10 km (about 6.25 miles) to access supercritical conditions. Drilling to this depth is financially prohibitive with existing technology. Economic production of supercritical resources will require the development of entirely new classes of: drilling technologies and methods; innovative stimulation approaches and techniques; and new production materials, processes, and equipment that can accommodate the extreme temperature, pressure, and chemical conditions of supercritical resources.

Supercritical geothermal resources contain geothermal fluids with high energy densities and low viscosities, improving and increasing their reservoir energy- and mass-flow characteristics (Elders et al. 2014). In many ways, supercritical geothermal resources are an extreme variant of the EGS resource spectrum. Because the resource characteristics, metrics, and tools required to model the full potential of supercritical resources are not yet fully developed, these resources could not be quantified as part of the EGS resource supply curves in the *GeoVision* analysis. Therefore, supercritical resources were not explicitly included in GETEM or ReEDS as a deployable resource for the *GeoVision* analysis.

The *GeoVision* analysis did, however, include case-study estimates of the supercritical resource potential of selected sites at a localized scale (Stimac et al. 2017, Doughty et al. 2018). The estimates from these local-scale assessments significantly exceeded that determined through EGS resource estimates for the same geographical site based on a broader, national-scale analysis (Augustine 2016). This finding highlights the potential of supercritical resources, assuming the development of technologies that enable economic production and effective well-targeting for such resources. The finding also suggests that more localized or site-specific resource estimates may identify EGS resource potential at higher levels than those determined through the national-scale estimates used in the *GeoVision* analysis.

Note: In thermodynamics, the “critical point” of a substance is the end point of a phase equilibrium curve separating a liquid and gaseous phase in terms defined by their pressure and temperature conditions. For pure water, the critical point occurs at 374°C and 220.64 bara (3,200 psia). Above the temperatures and pressures defined by the critical point, water exists as a supercritical fluid with unique properties characterized by high energy densities and low viscosities. Most natural systems contain water with salinities that move their critical points to temperatures of 400°C or beyond. Once supercritical conditions are encountered, innovative technologies will be required to develop those resources.

3.2.2 Non-Electric Sector Scenarios: Geothermal Heat Pumps

The GHP sector assessment of the *GeoVision* analysis used two primary scenarios—BAU and Breakthrough (BT). Because GHP deployment depends directly on

consumer behavior, the GHP sector assessment also integrated two market-adoption rates: Navigant Low and NREL Optimistic (Table 3-4). For the *GeoVision* analysis, both market rates were applied to each scenario. Additional detail on the inputs, assumptions, and characteristics for the GHP scenarios and adoption rates can be found in Liu et al. 2019 and Appendix C.

Geothermal Heat-Pump Sector Scenario	Main Characteristics
Current Installed Capacity (2012 Baseline)	<p>GHP Efficiency:</p> <ul style="list-style-type: none"> - Residential: 18.2 Energy Efficiency Ratio (EER)⁸⁵ 4 Coefficient of Performance (COP)⁸⁶ (at 100% load) - Commercial: 20 EER/4.2 COP (at 100% load) <p>Ground Heat Exchanger: \$14/foot</p> <p>Installed capacity as of 2012 was used as a baseline for comparison (Navigant 2013). A true BAU projection is difficult to determine for GHP, so for the purpose of impacts calculations (Chapter 4) the analysis of the model results calculated impacts of BT technology, cost reductions, and varying market adoption rates relative to the fixed 2012 baseline value.</p>
Business-as-Usual	<p>GHP Efficiency:</p> <ul style="list-style-type: none"> - Residential: 21.3 EER/4.7 COP by 2050 - Commercial: 23.4 EER/4.9 COP by 2050 <p>Ground Heat Exchanger: \$14/foot</p> <p>Includes all GHP deployment through 2012 as the starting point for the scenario. Projected growth is based on an assumed, moderate (17%) increase in operational efficiency for GHPs relative to conventional heating, ventilation, and air-conditioning systems by 2050 and depends on a chosen GHP market-adoption rate (see Table Note 1).</p>
Breakthrough	<p>GHP Efficiency:</p> <ul style="list-style-type: none"> - Residential: 27.3 EER/6 COP by 2030 - Commercial: 30 EER/6.3 COP by 2030 <p>Ground Heat Exchanger: \$9.80/foot by 2050</p> <p>Includes aggressive cost reduction and efficiency improvements resulting from technology improvement, with assumptions that the operational efficiency of GHP systems is improved by up to 50% by 2030, with no further improvements through 2050, and that the cost of ground heat exchangers is reduced by up to 30% by 2050.</p>
Geothermal Heat-Pump Market-Adoption Rates	Main Characteristics
Navigant Low	<p>dGeo deployment forecast based on consumer technology-adoption rates in Paidipati et al. 2008 as described and used in Navigant 2013 (see Table Note 2)</p>
NREL Optimistic	<p>dGeo deployment forecast based on historical adoption rate of solar photovoltaics developed by NREL (Sigrin and Drury 2013). This rate is higher than the Navigant rate (see Table Note 3).</p>

Table 3-4. Summary of Scenarios and Market Adoption Rates Used to Model Geothermal Heat-Pump Technology Deployment and Impacts

Table Notes: 1) Market-adoption rates are developed from comparative studies of the solar photovoltaics market. For the BAU scenario, the Navigant Low adoption rate is applied; the result is projected growth that is more conservative than historic GHP industry growth rates. 2) The Navigant Low adoption rate is based on a combination of insights from consumer surveys and market data for energy efficiency and heat pumps (Kastovich 1982). 3) After Sigrin and Drury 2014, the NREL Optimistic adoption curves were not influenced by policy incentives to any significant degree.

⁸⁵ Energy efficiency ratio (EER) is used to indicate the cooling efficiency of heat-pump equipment. EER is often expressed in Btu per hour/watt (i.e., Btu/hour of cooling for each watt of electrical input). The higher the EER, the more efficient the system.

⁸⁶ Coefficient of performance is the ratio of useful heating or cooling provided to the work required.

3.2.2.1 Business-as-Usual

The BAU scenario for GHPs started from a 2012 Deployment Baseline and assumed existing industry trends for technology advancement. The BAU scenario assumed little or no additional investment in GHP-related R&D and no additional financial incentives or tax credits for GHP installations. The scenario also assumed no cost reductions in ground heat exchangers and only moderate increases in the operational efficiency of GHP systems through 2050. The BAU scenario assumed no significant change in the cost or performance of competing conventional heating, ventilation, and air-conditioning (HVAC) technologies—which are already near their practical efficiency limits—during the same period (i.e., through 2050). The result is a 17% increase in efficiency difference between GHPs and conventional HVAC systems by 2050. The analysis assumed that the incremental cost increase for improving energy efficiency is offset by improvements in manufacturing efficiency and better economies of scale.

The BAU scenario further assumed no change in the costs or service lives of above-ground GHP equipment and baseline HVAC systems. Based on Kavanaugh et al. 2012, the installed cost of ground heat exchangers increased at an average annual growth rate of 2.65% from 1995 through 2012. This rate is slightly higher than the average annual U.S. inflation rate of 2.2% during the same period (Bureau of Labor Statistics, Consumer Pricing Index–All Urban Consumers, data extracted May 7, 2018). As such, the BAU scenario assumed that the real installed cost of ground heat exchangers is effectively constant over time. The dGeo model used an annual inflation rate of 2.5% to adjust costs in future years, through 2050.

3.2.2.2 Breakthrough

Similar to the TI scenario for the electric sector, the BT scenario for GHP incorporated technology improvements to reduce the costs and improve operating efficiencies of GHP systems. Improvements included lower costs of ground heat exchangers, as well as reduced cost and improved operating efficiency of GHP systems. The BT scenario assumed that the installed cost of ground heat exchangers is reduced up

to 30% by 2050. This reduction results from technical breakthroughs and better economies of scale from innovative business modes (e.g., utility-owned ground heat exchangers). The BT scenario also assumed that the average operational efficiency of GHP systems approaches the practical limit and improves 50% by 2030, with no further improvements through 2050.

3.2.2.3 Market-Adoption Rates

As noted previously and described in Table 3-4, *GeoVision* analysis modeling for the GHP non-electric sector included two market-adoption rates intended to simulate and account for uncertainties in consumer behavior. The maximum market potential of GHPs in each scenario was determined using two different empirical correlations: one from Navigant (Navigant Low) (Paidipati et al. 2008) and the other from NREL (NREL Optimistic) (Sigrin and Drury 2014). The Navigant Low adoption rate is based on a combination of insights from consumer surveys and market data for energy efficiency and heat pumps (Kastovich 1982), whereas the NREL Optimistic rate is based on market-adoption data for distributed solar photovoltaics.



Helicopter-supported geothermal exploration drilling on Akutan Island, Alaska. Photo credit: Neil McMahon

Figure 3-3 illustrates the Navigant Low and NREL Optimistic market-adoption curves that are applied to each of the BAU and BT GHP scenarios. The market-adoption curves reflect correlations between the maximum market-adoption potential (i.e., number of consumers who would eventually adopt the technology) and the investment payback period. Incentives could reduce the costs that a consumer might pay for a given technology, thus reducing the payback period and increasing the maximum market potential. Incentives will not, however, change the adoption curve itself because the relationship between the payback and market potential is static. Market-adoption curves may not be sensitive to technology type because the curves depend on the simple payback of a potential investment, irrespective of the technology in question.

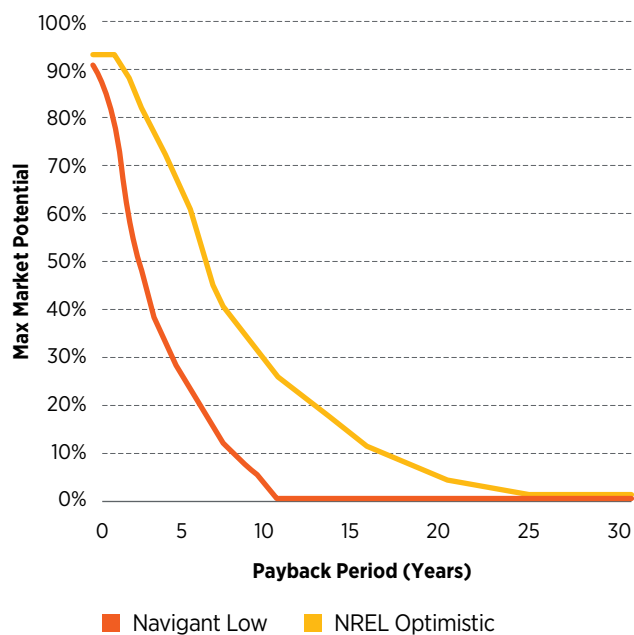


Figure 3-3. Market-adoption curves used in the *GeoVision* analysis and applied to geothermal heat-pump modeling scenarios within dGeo

Source: Liu et al. 2019

Figure Note: In each model year, the maximum market potential—i.e., the fraction of viable GHP systems that would eventually be implemented given the technical and economic conditions—is calculated based on the GHP investment payback period.

3.2.3 Non-Electric Sector Scenarios: *Geothermal Direct Use (Geothermal District Heating)*

The geothermal direct-use assessment for the *GeoVision* analysis used two primary scenarios: Business-as-Usual and Technology Improvement (Table 3-5). Technology cost and performance assumptions for identifying and accessing geothermal direct-use resources are similar to those assumed for electric-sector scenarios of the same name. As discussed in Section 3.1.3 and in McCabe et al. 2019, it was only possible to explore the economic potential—and not the full market-deployment potential—of geothermal direct-use applications for geothermal district heating. Therefore, the *GeoVision* analysis restricted the market-based deployment potential and associated impacts for the non-electric sector to the GHP sector and did not assess this information for geothermal district heating.

For both district-heating scenarios shown in Table 3-5, the resource potential in dGeo is based on a 2016 NREL study (Mullane et al. 2016) investigating the location, temperature, and amount of stored heat of low-temperature (<150°C) and relatively shallow (<3,000 meters) hydrothermal and EGS resources in the United States. Including EGS as a direct-use resource greatly increases the size and geographic reach of district-heating resource potential. Appendix C provides more detail on inputs and assumptions for geothermal district heating.

Geothermal District-Heating Sector Scenario	Main Characteristics
Business-as-Usual	Established as a baseline for comparison purposes. Includes all geothermal direct-use deployment through 2016. Incorporates existing and anticipated values of technical, cost, and financial parameters of geothermal district-heating systems, assuming similar market conditions for the next 30 years or more and no investments to improve technology or financing.
Technology Improvement	Includes cost reductions and technology advances resulting from technology improvements used in the electric-sector TI scenario. Improvements over BAU include: 1) a 50% reduction in drilling costs, 2) an increase in EGS well flow rate from 40 kg/s to 110 kg/s, 3) an average 15% decrease in exploration-related costs, and 4) a 50% improvement in EGS resource-recovery factors (2% to 3%). Also assumes a 32% decrease in discount rate for project financing (weighted-average cost of capital reduced from 2.8% to 1.9%). Improvements are modeled to occur gradually (linearly) from 2016 to 2030 and stay constant through 2050.

Table 3-5. Summary of Scenarios Used to Model Non-Electric-Sector, Geothermal Direct-Use/Geothermal District-Heating Technology Economic Potential

Table Notes: McCabe et al. 2019 provides a full discussion of geothermal direct-use scenarios



CHAPTER FOUR

GeoVision Analysis: Results, Opportunities, and Impacts

Grand Prismatic Spring in Yellowstone National Park, Wyoming.

Photo credit: Jim Stimac

4 *GeoVision* Analysis: Results, Opportunities, and Impacts

As discussed in Chapter 3, the *GeoVision* analysis used detailed, quantitative models to assess geothermal deployment potential under scenarios that consider a range of technologies, market conditions, and barriers. Chapter 3 summarized the *GeoVision* modeling analytics and approach. Chapter 4 presents the modeling results, discusses key takeaways, and presents a summary of impacts to the nation from the levels of geothermal energy deployment projected in the *GeoVision* analysis. Among other findings, the results indicate that geothermal electricity-generation capacity can double based on regulatory reforms alone and that enhanced geothermal systems (EGS) have the potential to supply more than 16% of U.S. electricity generation and support the economic potential for as many as 17,500 district-heating installations by 2050. Findings also indicate that the market potential for geothermal heat-pump technologies is equivalent to supplying heating and cooling solutions to 28 million households. Achieving the levels of deployment discussed in this chapter will require actions aimed at pursuing technology innovations, reducing costs, and overcoming barriers. These actions are discussed in the *GeoVision* Roadmap (Chapter 5).

4.1 Deployment Potential—Electric Sector

The *GeoVision* analysis included modeling of geothermal technology deployment within the electricity market sector for conventional hydrothermal and EGS resources. As discussed in Section 3.2.1, the *GeoVision* analysis included assessing electric-sector opportunities under three primary scenarios: Business-as-Usual (BAU), Improved Regulatory Timeline (IRT), and Technology Improvement (TI). One key finding in the electric-sector modeling is that regulatory reforms assumed in the IRT scenario alone could double the size of installed geothermal capacity through increased access to and development of

conventional hydrothermal resources. Additionally, the analysis indicates that improved exploration and drilling technologies envisioned in the TI scenario can assist across the board in the industry's ability to maximize resource capture—including up to 60 gigawatts-electric (GW_e) of electricity-generating capacity by 2050. The most promising growth potential can be realized by advancing early-stage research and development into technologies that support EGS.

4.1.1 Deployment Potential in the Business-as-Usual and Improved Regulatory Timeline Scenarios

The *GeoVision* analysis BAU scenario reflected industry trends and the anticipated future if the industry continues on the same path as 2016 conditions. Results indicate that, under the BAU scenario, installed geothermal net-summer capacity increases from 2.5 GW_e to 6 GW_e by 2050. This result is consistent with existing growth trends in the geothermal industry (Augustine et al. 2019). The BAU scenario serves as the baseline for assessing the impact of other scenarios considered in the *GeoVision* analysis and related studies (Wendt et al. 2018, Millstein et al. 2019, Young et al. 2019).



The Hoch and Vulcan geothermal power plants in California coexist amidst the existing land use.

Photo credit: Martin J. Pasqualetti

The IRT scenario assessed the effect of potential regulatory reforms that could reduce geothermal development timelines by half and triple rates of geothermal exploration and resource discovery. The deployment potentials calculated under the IRT scenario were compared to the BAU scenario to determine the effect regulatory reform alone could have on geothermal development. The results indicate that—using existing geothermal technologies—the geothermal industry could double in size relative to BAU through only regulatory reform (Figure 4-1). The total deployment resulting under the IRT scenario is nearly 13 GWe by 2050—more than a 5-fold increase over existing installed geothermal capacity and double the installed capacity in 2050 under the BAU scenario. The IRT scenario assumed that applicable regulatory reforms are legally allowed and appropriate for the respective situation.

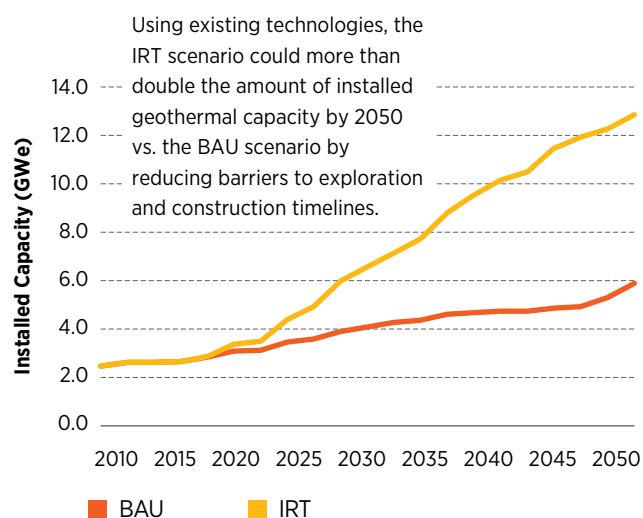


Figure 4-1. Improved Regulatory Timeline scenario results and comparison to the Business-as-Usual scenario for conventional hydrothermal resources

Figure Note: The IRT scenario projects that the geothermal industry could double in size by 2050 compared to the BAU scenario by reducing exploration barriers and construction timelines via regulatory reform. Total deployment in the IRT scenario would reach nearly 13 GWe by 2050.

The IRT scenario assumed that EGS technologies do not advance beyond existing levels; as such, EGS resources are not commercially viable nor deployed in the Regional Energy Deployment System (ReEDS) model under the IRT scenario. As is the case in the BAU scenario, growth achieved under the IRT scenario is

supported entirely by the development of conventional hydrothermal resources, the majority of which are undiscovered hydrothermal resources (Figure 4-2). Exploration that supports conventional hydrothermal resource growth in the IRT scenario results from shorter permitting timelines, which enhance developer access to resources and increase the amount of exploration that can be performed in a given time period.

Results of the *GeoVision* analysis indicate that—using existing geothermal technologies—the geothermal industry could double in size relative to Business-as-Usual through only regulatory reform.

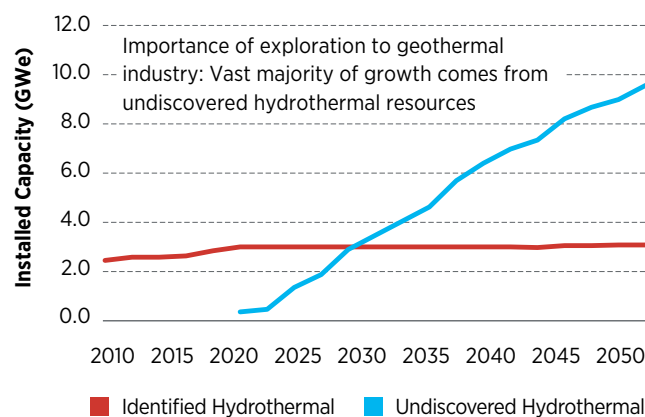


Figure 4-2. Improved Regulatory Timeline deployment results by resource type

Figure Note: Undiscovered hydrothermal resources constitute the majority of the resource capture, which supports overall growth (identified and undiscovered) to about 13 GWe total (Augustine et al. 2019).

The increased amount and ease of conducting exploration activities under the IRT scenario is assumed to triple discovery rates for undiscovered hydrothermal resources—from 1% to 3% of the total undiscovered resources per year compared to the BAU scenario (Table 3-1). Moreover, the IRT scenario assumes the use of existing exploration technologies. To maximize growth potential across all scenarios, the industry will need to improve exploration technologies so that greater amounts of the undiscovered resource

base may be discovered and developed. This result highlights the importance of exploration for facilitating geothermal industry growth and the potential for improved exploration technologies to further advance that growth. When combined with improvements in regulatory timelines, resource access, and drilling technologies, improved exploration technologies present important pathways toward achieving the full deployment potentials identified in the *GeoVision* analysis TI scenario (Section 4.1.2). Actions related to achieving such improvements are discussed in the *GeoVision* Roadmap (Chapter 5).

4.1.2 Deployment Potential in the Technology Improvement Scenario

The *GeoVision* TI scenario models the most aggressive and optimistic scenario assumptions and the resulting cost reductions that can drive geothermal deployment. The TI scenario shows particular promise for EGS resource deployment, which stands to benefit substantially from improved technology and reduced capital costs (Table 3-3). The results of the TI scenario indicate the potential for more than 60 GW_e of geothermal power generation net summer capacity, the majority of which would come from deep-EGS resources after 2030 (Figure 4-3). As explained in Section 2.2.1, net summer capacity is defined by the Energy Information Administration (EIA) as, “The maximum output, commonly expressed in MW, that generating equipment can supply to system load, as demonstrated by a multi-hour test, at the time of summer peak demand (period of June 1 through September 30).”

The levels of deep-EGS deployment shown in Figure 4-3 would require hundreds to more than 1,000 wells to be drilled annually to support EGS project developments. By comparison, the oil and gas industry has been drilling hundreds to more than 1,000 horizontally oriented and hydraulically fractured wells per month (EIA 2018).

With the technology improvements modeled in the TI scenario, geothermal power production could support up to 8.5% of total national generation by 2050, as

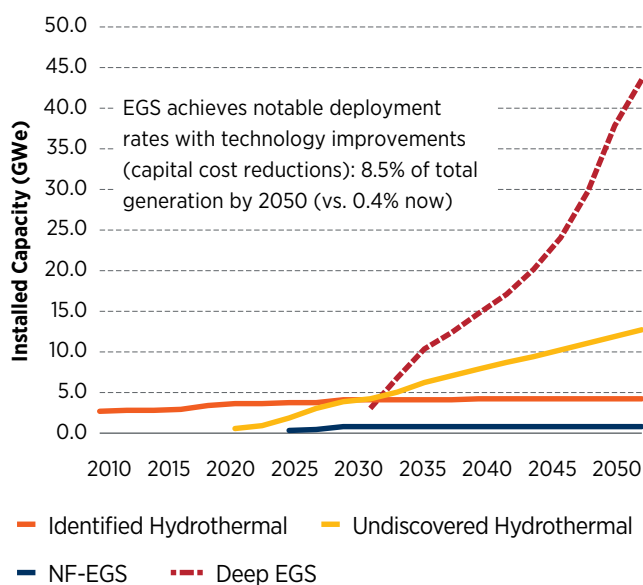


Figure 4-3. Technology Improvement scenario results by resource type

Figure Note: The TI scenario incorporates technology improvements and the resulting cost reductions that drive additional deployment. At the end of the analyzed period (2050), total geothermal deployment in the TI scenario is more than 60 GW_e, with the majority of growth supplied by deep-EGS resource development after 2030 (Augustine et al. 2019). NF-EGS is near-field EGS.

With technology improvements considered in the *GeoVision* analysis, geothermal power production could support up to 8.5% of total national generation by 2050, as compared to the 0.4% share of total national generation contributed by the existing geothermal industry today.

compared to the 0.4% share of total national generation contributed as of 2017 (Augustine et al. 2019).

Figure 4-4 shows terawatt-hour generation by year within the renewable power sector for the *GeoVision* TI scenario. The results in Figure 4-4 are split into two categories: 1) baseload renewable power—which includes geothermal, hydropower, biopower, and concentrated solar power—and 2) variable-generation renewable power. In the TI scenario, geothermal energy could provide about 57% of the entire baseload renewable power-generation portfolio.⁸⁷

⁸⁷ Baseload renewable power includes geothermal, hydropower, biopower, and concentrated solar power.

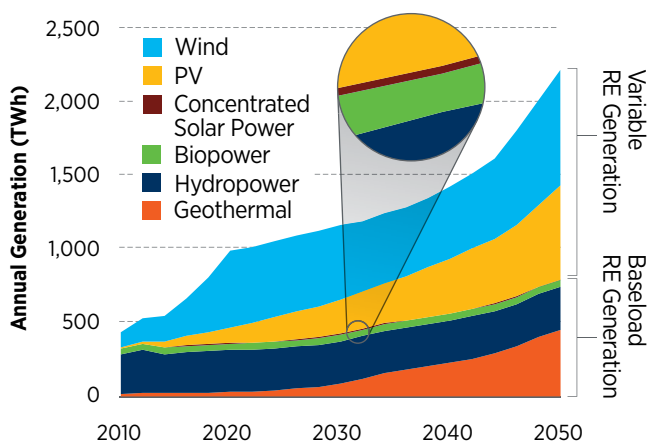


Figure 4-4. Total national generation (terawatt-hours) for the renewable energy (RE) market sector by year for the *GeoVision* Technology Improvement scenario

Figure Note: The right vertical axis divides the sector into baseload renewable power—which includes geothermal, hydropower, biopower, and concentrated solar power—and variable-generation renewable power. Geothermal power could provide about 57% of the **baseload** RE generation portfolio by 2050 (or 20.4% of all RE generation). Biopower includes landfill-gas generators, co-fired biomass/co-fired coal, and biomass/dedicated biomass. PV is solar photovoltaic.

The *GeoVision* analysis also evaluated “alternative future” combined scenarios that assess the TI scenario combined with the ReEDS Standard Scenarios.⁸⁸ This approach facilitated assessments of external factors—such as electricity demand, fuel prices, technology costs, resource and system constraints, and others—and how those factors combined with technology improvements might change geothermal deployment. One of the combined scenarios that demonstrates potential for geothermal deployment beyond that achievable under the TI scenario alone is summarized in Table 4-1. This particular combined scenario considers the TI scenario in combination with the ReEDS “High Natural Gas Prices” Standard Scenario, which uses scenario projections from the EIA’s Annual Energy Outlook 2016. The combined scenario considers a possible future where both the TI scenario assumptions are true and natural-gas prices are assumed to be higher than the 2016 Annual Energy Outlook Reference case for natural-gas projections by using the 2016 Annual Energy Outlook “Low Oil and Gas

Resource and Technology” case (Cole et al. 2016b, EIA 2016, Augustine et al. 2019). As noted, the combined scenario represents a possible future situation where geothermal deployment is higher than under the TI scenario alone. The full assessment of combined scenarios considered in the *GeoVision* analysis is summarized in Appendix C and detailed in Augustine et al. 2019.

Scenario	Varied Assumptions	Consistent Assumptions Across Scenarios
TI	None (Mid-case scenario)	Capital and O&M Costs: TI
TI + High Natural-Gas Prices	Future with high natural-gas costs (AEO 2016)	Construction Time, Hydrothermal: 4 years Construction Time, EGS: 5 years Financing: ReEDS Standard WACC (8%)

Table 4-1. Technology Improvement Scenario Combined with a Regional Energy Deployment System Standard Scenario

Table Notes: (1) The combined scenario described here forms the basis for a potential future that has high natural-gas costs in accordance with the AEO’s Low Oil and Gas Resource and Technology case (EIA 2016). (2) WACC = weighted-average cost of capital; O&M = operations and maintenance; AEO = Annual Energy Outlook.

Using the combined scenario assumptions in Table 4-1, geothermal deployment levels reach nearly 120 GWe by 2050 (Figure 4-5) (Augustine et al. 2019). The geothermal technology deployment potentials calculated in the combined scenario comprise less than 10% of total U.S. installed capacity, but would provide over 16% of the country’s total generation due to the high capacity factor of geothermal technologies. For the combined scenario, additional deployment compared to the TI scenario alone comes primarily from deep-EGS resources. The amount of installed geothermal capacity expands due to improved

⁸⁸ The Standard Scenarios are a suite of forward-looking power-sector scenarios that are used within the ReEDS capacity-expansion model (Cole et al. 2016a). The scenarios encompass Earth-system feedbacks, electricity demand growth, electricity generation, existing fleet retirements, fuel prices, the policy and regulatory environment, resource and system constraints, and technology costs. Together, the Standard Scenarios make possible the transparent and quantitative examination of how various inputs impact power-sector development. Moreover, they provide context and data to support understanding of changes in the U.S. power sector and inform stakeholder decision making about its future direction. The Standard Scenarios (Cole et al. 2016a), which are updated each year along with the Annual Technology Baseline, include technology cost and performance assumptions from the Annual Technology Baseline (Cole et al. 2016b).

economic conditions for geothermal (in this case, as higher prices for natural gas). This finding suggests that, under the conditions modeled in the *GeoVision* analysis, geothermal energy growth is limited by the conditions that drive demand for geothermal development and not by resource potential.

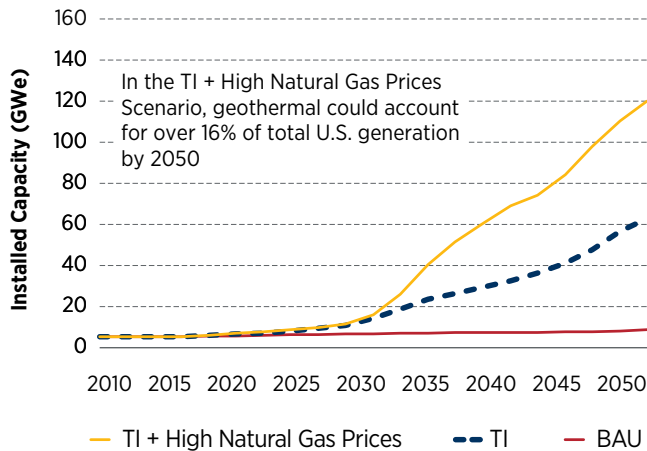


Figure 4-5. Installed geothermal capacity for Technology Improvement scenario compared to a combined scenario and Business-as-Usual

Figure Note: The combined scenario considers the TI scenario in combination with the ReEDS “High Natural Gas Prices” Standard Scenario, which uses scenario projections from the EIA’s Annual Energy Outlook 2016. The combined scenario considers a possible future where both the TI scenario assumptions are true and natural-gas prices are assumed to be higher than the 2016 Annual Energy Outlook Reference case for natural-gas projections by using the 2016 Annual Energy Outlook “Low Oil and Gas Resource and Technology” case (Cole et al. 2016b, EIA 2016, Augustine et al. 2019). Appendix C provides additional detail. The combined scenario is compared to the BAU scenario and the TI scenario alone. The TI scenario alone drives greater capacity deployment starting around 2020, with greater growth starting in 2030 from deployment of more deep-EGS resources. The TI + High Natural Gas Prices combined scenario shows similar growth starting in 2030, but grows at a higher rate than the TI scenario alone through 2050. This result indicates that EGS growth is limited by demand and not supply.

4.2 Deployment Potential—Non-Electric Sector

The *GeoVision* analysis assessed opportunities for two non-electric-sector geothermal applications: geothermal direct use for district heating, and geothermal heat pumps (GHPs). Findings illustrate national opportunities for non-electric uses of geothermal energy, with the potential for more than

Under a scenario that combined the *GeoVision* analysis Technology Improvement scenario with high natural-gas prices, geothermal deployment levels can reach nearly 120 GWe by 2050. The deployment potentials for this scenario comprise less than 10% of total U.S. installed capacity, but would represent more than 16% of the country’s total generation due to the high capacity factor of geothermal energy.

17,500 geothermal district-heating system installations and a more than 11-fold increase in installed GHP capacity (relative to a 2012 baseline).

The *GeoVision* analysis used the Distributed Geothermal Market Demand (dGeo) model for the non-electric sector analysis (Section 3.1.3), and included scenarios for improved technology and—in the case of GHPs—consumer-adoption behaviors. The analysis is summarized in Sections 4.2.1 and 4.2.2 and detailed in McCabe et al. 2019 and Liu et al. 2019.

4.2.1 Deployment Potential of Geothermal Direct Use for District Heating

As noted in Chapter 2 (Figure 2-7), there is an immense array of end-use opportunities for geothermal direct-use applications, including agricultural and industrial uses where process heat is required. The *GeoVision* analysis for direct-use applications focused on district heating, which is the most widespread geothermal direct-use application (Lund and Boyd 2015) and which addresses an area of high energy demand: residential and commercial heating at a district scale. The *GeoVision* analysis did not consider district cooling.

Market-potential-based assessments for the geothermal non-electric sector using the dGeo model rely on data about the behavior of individual consumers and their willingness to adopt a technology based on payback period. As explained in Sections 3.2.2 and 3.2.3, geothermal district-heating technologies are deployed

by communities whose decision to approve and adopt such installations is complicated by many factors beyond the payback period. As such, the *GeoVision* analysis considered only economic potential for geothermal district heating. As discussed in Chapter 3, economic resource potential represents the portion of total technical potential that is cost effective to recover based on technology costs and anticipated revenues.

The *GeoVision* analysis reports economic potential for geothermal district heating in relation to both the associated conventional hydrothermal and EGS resource bases (i.e., technical and resource potential) and the local demand for district heating (i.e., population density and climate). EGS resources are available over a larger geographic area and represent about 1,000 times more resource potential compared to the corresponding hydrothermal resource potential (McCabe et al. 2019) (Figure 4-6).

The *GeoVision* analysis identified national economic potential for geothermal district heating and confirms that the highest economic potential is co-located with cost-effective resource availability and concentrated heating demand. The economic potential for geothermal district-heating systems using geothermal direct-use resources is more than 17,500 installations nationwide—totaling 320 GW_{th} of heating capacity—with pronounced potential in the Northeast corridor of the United States. Figure 4-7 indicates the most favorable economic potential for geothermal district heating throughout the United States under the *GeoVision* analysis BAU scenario (top left) and under the *GeoVision* TI scenario (top right) (Table 3-5). This economic potential enables cost-competitive development of EGS resources. Both maps include conventional hydrothermal as well as EGS resources. Comparing the economic potential maps to the image of the United States at night (Figure 4-7, bottom left) illustrates the geographic alignment of the widespread EGS resource base and demand centers—discrete population centers that can benefit from geothermal district-heating systems.⁸⁹

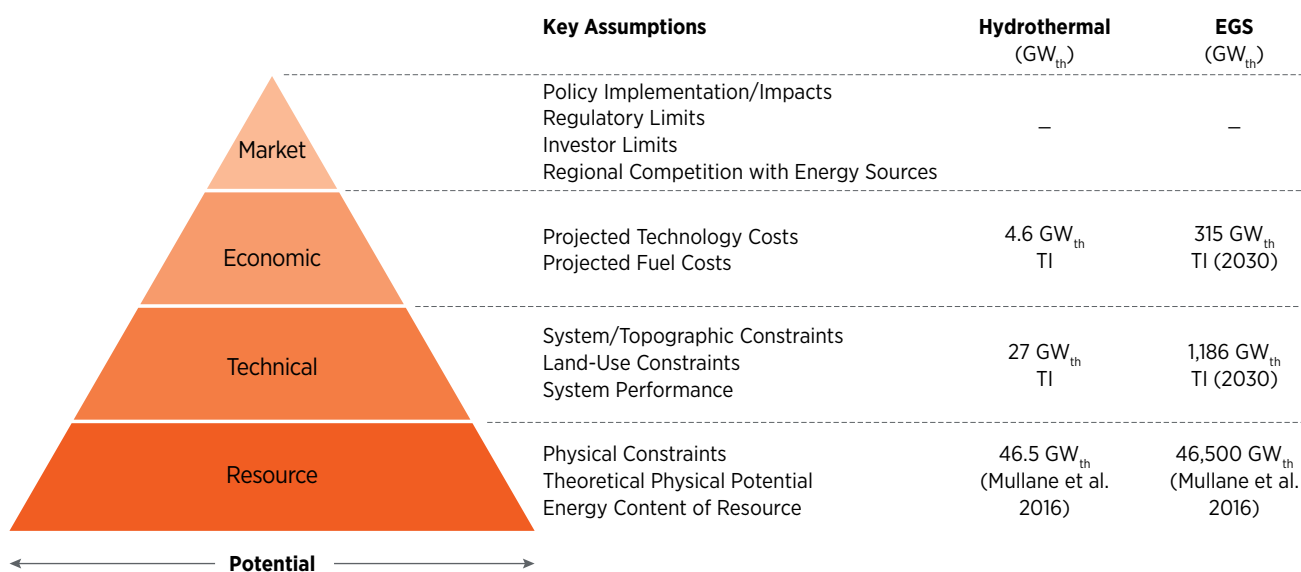


Figure 4-6. Geothermal district-heating deployment potential supported by hydrothermal and enhanced geothermal system resources as a function of resource, technical, and economic potential under the *GeoVision* analysis Technology Improvement scenario

Source: McCabe et al. 2019

Figure Note: Information about district-level consumer behavior for the U.S. geothermal direct-use/geothermal district-heating market was insufficient to enable modeling on the scale of the market potential. The *GeoVision* analysis assumes that EGS technologies become commercially feasible starting in 2030. “TI” in the Hydrothermal and EGS columns refers to the *GeoVision* analysis Technology Improvement scenario for geothermal district heating (Section 3.2.3). GW_{th} = gigawatts-thermal.

⁸⁹ Population centers or groups may include building complexes such as hospitals and campuses. In locations where buildings are more dispersed, district-heating systems would be less cost effective to deploy due to piping costs.

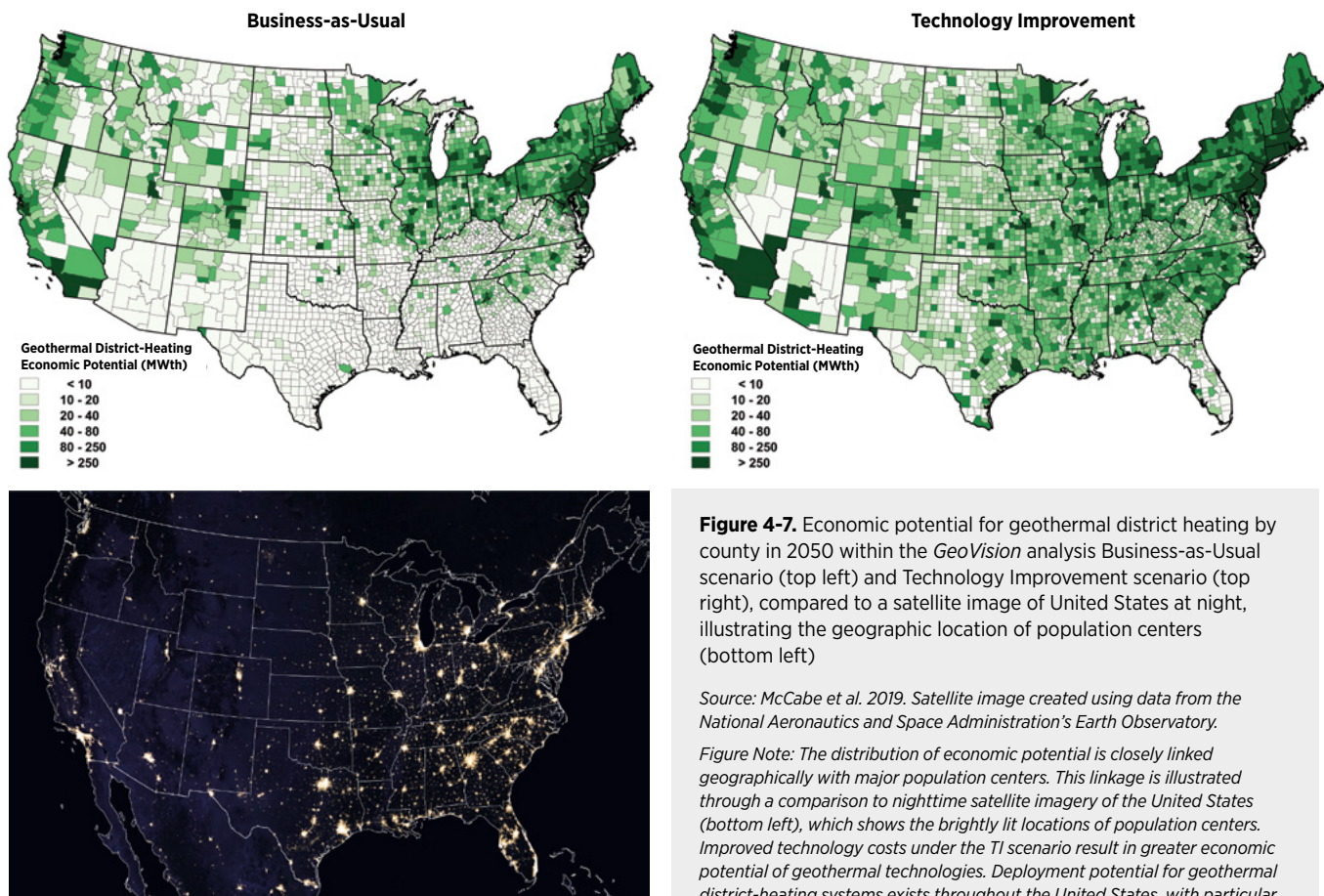


Figure 4-7. Economic potential for geothermal district heating by county in 2050 within the *GeoVision* analysis Business-as-Usual scenario (top left) and Technology Improvement scenario (top right), compared to a satellite image of United States at night, illustrating the geographic location of population centers (bottom left)

Source: McCabe et al. 2019. Satellite image created using data from the National Aeronautics and Space Administration’s Earth Observatory.

Figure Note: The distribution of economic potential is closely linked geographically with major population centers. This linkage is illustrated through a comparison to nighttime satellite imagery of the United States (bottom left), which shows the brightly lit locations of population centers. Improved technology costs under the TI scenario result in greater economic potential of geothermal technologies. Deployment potential for geothermal district-heating systems exists throughout the United States, with particular potential concentrated along the Northeast Corridor. The total economic potential for geothermal district-heating systems using geothermal direct-use resources is more than 17,500 installations nationwide.

As is the case for geothermal electricity-generation applications, deployment growth for geothermal direct-use applications such as geothermal district heating will require improved technologies that lower the costs of EGS resource development.

4.2.2 Deployment Potential for Geothermal Heat Pumps

As noted in Section 3.2.2 and Table 3-4, the *GeoVision* analysis looked at two primary scenarios for the GHP market: 1) a Business-as-Usual (BAU) scenario, and 2) a Breakthrough (BT) scenario. In the BT scenario, technology improvements reduce ground heat-exchanger costs by 30%, and improve operational efficiency of GHP systems by 50%. Liu et al. 2019 provides more detail about the GHP analysis.

Figure 4-8 illustrates geographically the economic potential for GHP systems under the *GeoVision* analysis BAU and BT scenarios. Under both scenarios, economic potential is most concentrated in the Northeast and Midwest, with New York, Pennsylvania, Illinois, Ohio, and Michigan showing the highest potential—more than 174 gigawatts-thermal (GW_{th})⁹⁰ combined for the BT scenario.

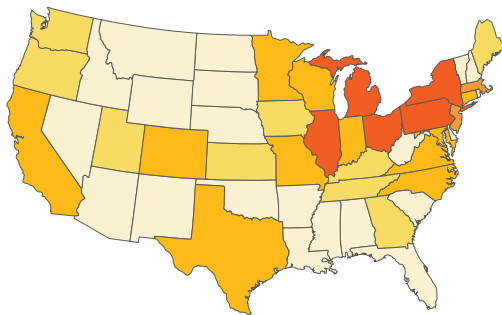
Similar to the case for geothermal direct use, the economic potential for GHP systems is the portion of total technical potential that can be deployed where it can provide lower-cost heating and cooling alternatives for consumers. Economic potential is driven by capital costs and fuel costs and can vary with time as these factors change. Economic potential is higher than market potential because market potential is affected

90 Gigawatts-thermal is power available directly in the form of heat, as opposed to gigawatts-electric, which is power available in the form of electricity generated from the conversion of heat or other potential energy.

BAU Scenario

State 2050

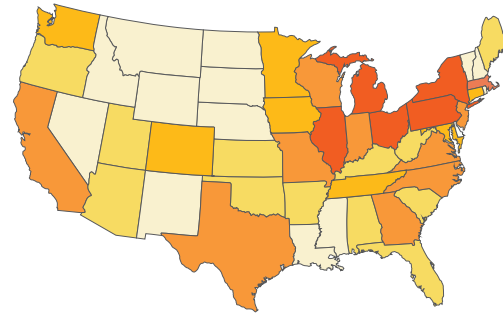
NY	40.3
IL	28.6
PA	28.5
MI	26.7
OH	26.5
NJ	19.3
MA	19.1
CA	14.5
IN	13.8
VA	13.0



BT Scenario

State 2050

NY	44.9
PA	34.1
IL	32.7
OH	31.8
MI	30.7
CA	24.1
TX	22.5
NJ	22.4
MA	20.8
NC	18.4



GHP Potential (GWth)

< 5
 5-10
 10-15
 15-25
 > 25

Figure 4-8. Economic potential for geothermal heat-pump systems by state in 2050 under the Business-as-Usual (left) and Breakthrough (right) scenarios, with the top 10 states listed separately

by conditions such as the regulatory environment, consumer understanding of the technology, and competing alternatives. GHPs are used at the individual consumer level, so market potential is affected heavily by consumer interest and understanding of the technology and its benefits. Consumer behavior also determines the speed at which full market potential is captured, determining the rate of capacity deployment at any given time. In theory, the capacity-deployment and market-potential curves will eventually meet, and consumer-adoption rates essentially determine how quickly that happens.

Figure 4-9 illustrates the economic-potential results for GHPs under the BAU and BT scenarios, as well as the related market potential and capacity deployment. The *GeoVision* analysis considered two consumer-adoption rates (Liu et al. 2019). Figure 4-9 assumes the more optimistic consumer-adoption rates, under which people are more likely to purchase a GHP system for a given payback period, and is based on adoption profiles observed within the solar photovoltaics market (Section 3.2.2 and Table 3-4).

The *GeoVision* analysis concludes that market potential for geothermal heat pumps is more than 14 times larger than existing capacity. This potential could translate to heating and cooling for about 28 million U.S. homes.

Using the more optimistic consumer-adoption rate (NREL Optimistic), the BAU and BT scenarios both show significant GHP market potential, underscoring the importance of GHP technologies to the U.S. heating and cooling market. The *GeoVision* analysis concluded that the maximum GHP **market potential** in the BT scenario—resulting from technology breakthroughs and assumptions of the “NREL Optimistic”⁹¹ consumer-adoption rates—is more than 14 times larger than existing capacity. This result is equivalent to heating and cooling solutions for about 28 million homes, compared to the installed GHP capacity equivalent of roughly 2 million homes at the time of the *GeoVision* analysis.⁹² This potential represents about 23% of the total residential heating and cooling market share by 2050. From this market potential, total actual capacity deployment in 2050 is projected to be enough to support about 18.6 million U.S. homes.

⁹¹ NREL is the National Renewable Energy Laboratory.

⁹² According to Lund and Boyd (2016), the installed capacity of GHPs in the United States had increased to 16.8 GW_{th} (or about 5 million cooling tons) by 2016. A GHP capacity equivalency of 1.92 million homes was determined on the basis of a calculated average size of residential GHP systems as 2.5 tons (8.75 kilowatts-thermal [kW_{th}]) per household. This average size was derived assuming an average U.S. household floor space of 1,750 square feet and an average U.S. household heating, ventilation, and air-conditioning size of 700 square feet/ton (DOE 2010, Moura et al. 2015).

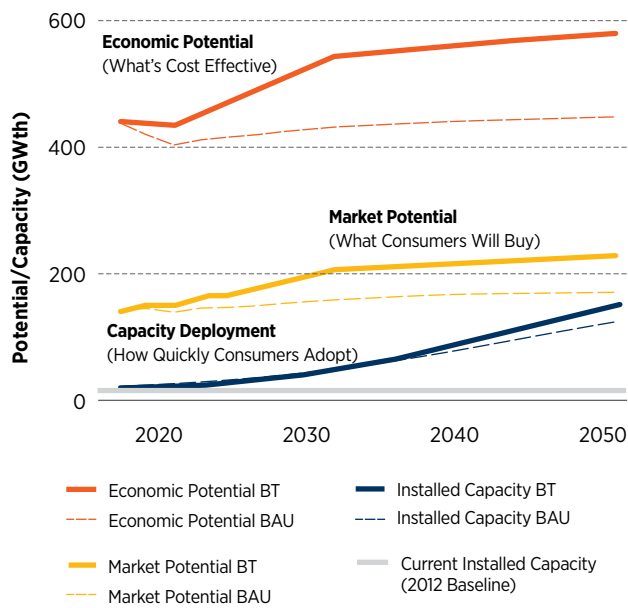


Figure 4-9. Geothermal heat-pump potential under the Business-as-Usual (denoted BAU) and Breakthrough (denoted BT) scenarios assuming the NREL Optimistic consumer-adoption rate

Figure Notes: The chart illustrates that GHP capacity deployment is lower than the economic and market potential because the speed at which deployment occurs is a function of consumer behavior. The reduced rate of increase after 2030 in the economic and market potentials is driven by changes in costs over time. Beyond 2050, the curves of capacity deployment and market potential will eventually meet, driven by consumer-adoption rates. Installed capacity as of 2012 (“2012 Baseline”) was used as a baseline for comparison (Navigant 2013). NREL is the National Renewable Energy Laboratory.

The *GeoVision* analysis confirms that technology improvements are a significant factor in advancing GHP deployment. The geothermal industry could also benefit from improved financing and business structures, as well as enhanced collaboration, education, and outreach that help provide consumer knowledge. For GHPs, greater consumer understanding could lead to more and earlier adoption of the technology, converting more economic potential into market potential. Results of the full *GeoVision* analysis for GHPs are detailed in Liu et al. 2019.

4.3 The Market and Technology Nexus

The *GeoVision* analysis indicates that the market for conventional hydrothermal resources and their proven technology applications in electric-power generation have the potential to double in capacity through regulatory reform alone, relative to BAU. In the longer term, EGS resources hold the potential to supply more than 8.5% of the nation’s total electric-power generation by 2050. In the *GeoVision* modeling scenario that considers improved technologies (the TI scenario), in combination with the ReEDS Standard Scenario that includes high natural-gas prices, EGS resources have the potential to provide more than 16% of the country’s total generation by 2050 (Augustine et al. 2019).

For the heating and cooling sector, the *GeoVision* analysis indicates an opportunity to deploy GHP systems in 28 million homes (versus roughly 2 million residential GHP systems nationwide as of 2016). The *GeoVision* analysis also confirms that, by 2050, about 320 GW_{th} of geothermal direct-use resources are available to be economically deployed through improved technologies that enable EGS development. If deployed as geothermal district heating, these 320 GW_{th} could support as many as 17,500 geothermal district-heating installations across the United States—sufficient to satisfy the demand of about 45 million households.⁹³

By identifying deployment opportunities across a range of geothermal applications and end uses that are at varied levels of maturity, the *GeoVision* analysis provides a view of the geothermal industry’s nexus of markets and technologies. Figure 4-10 illustrates the differentiation between the markets for existing, proven technologies and those that require developing technologies and primarily use EGS resources. The *GeoVision* analysis confirms significant growth opportunities for both types, along different pathways. For proven technologies, industry growth to maximum deployment will require stakeholders to collectively address barriers related to project financing, regulatory

⁹³ The Energy Information Administration estimates that there are 118 million homes in the U.S. residential sector (Energy Information Administration 2015). Using this value plus data from the *GeoVision* analysis related to existing GHP market share and installed capacity indicates that 1 GW_{th} can supply heat to about 140,000 homes on average. This value was used to determine the impact of 320 GW_{th} of direct-use capacity on U.S. homes.





Electricity		Heating/Cooling	
<p>Proven Technology Focus: Financing, Regulations, Outreach, Policy</p>	 <p>Conventional Hydrothermal Double size of industry by regulation reform</p>	 <p>GHP 2 million installed vs. 28 million potential</p>	
<p>Developing Technology Focus: R&D, Technology Advancements</p>	 <p>EGS 8.5% of total generation by 2050 (20.4% of all RE generation)</p>	 <p>Direct Use (EGS) 0.1 GW installed vs. 320+ GW potential</p>	

Figure 4-10. The *GeoVision* analysis market-technology nexus

*Figure Note: The primary geothermal market sectors are electricity and heating and cooling. The electric sector is served by proven and cost-effective conventional hydrothermal resource technologies and by developing EGS technologies. The heating and cooling sector is served by proven GHP technologies and direct-use applications such as geothermal district heating supported by both conventional hydrothermal resources—and, eventually, EGS technologies. Proven technologies face greater development and implementation obstacles in the areas of financing, regulatory timelines, outreach, and market structures, whereas developing technologies require a focus on research and development to support technology advancements. Installed and potential values under GHP and direct use refer to market potential and economic potential, respectively. As discussed in this chapter, deployment of geothermal district heating based on market potential could not be modeled in the *GeoVision* analysis.*

timelines, outreach and education, and market structures. For *unproven* and *developing* geothermal technologies, deployment growth will be advanced most effectively through research, development, and technology advancement. Actions to advance pathways for both proven and unproven technologies are discussed in the *GeoVision* Roadmap (Chapter 5).

4.4 Impacts of the *GeoVision* Analysis Findings

The *GeoVision* analysis included an assessment of impacts resulting from increased geothermal deployment—jobs and economic development in the domestic geothermal sector as well as water use and air emissions. Most of the impacts were examined at a national scale, with job impacts also evaluated regionally. Sections 4.4.1–4.4.3 summarize the impacts modeling and results, which are based on modeled deployment potentials for the electric and non-electric sectors as described in Sections 4.1–4.3. Impacts were

evaluated independently for each sector using the results from the deployment modeling scenarios. Unless otherwise indicated, impacts are expressed as the difference between existing conditions and the various *GeoVision* analysis scenarios. Details of the impacts assessment are in Millstein et al. 2019.

Impacts assessments for power generation in the electric sector correspond to the deployment potential analysis of the Business-as-Usual, Improved Regulatory Timeline, and Technology Improvement scenarios. For the electric sector, impacts were calculated as the difference in specific outcomes (e.g., water consumption) between the BAU scenario and each of the other two scenarios (IRT and TI). For GHPs in the non-electric sector, impacts were calculated as the difference between a 2012 installed-capacity baseline with no additional GHPs (Liu et al. 2019) and the two technology scenarios—BAU and BT—in combination with two market-adoption rates: Navigant Low and NREL Optimistic (Table 3-4).⁹⁴

⁹⁴ The 2012 Baseline was chosen within the dGeo model framework to allow for assessment of the benefits of the growth in the GHP sector under both the Navigant and NREL adoption rates. This was accomplished by quantifying the benefits vs. the level of GHP deployment at the beginning of the dGeo model run. This initial level of GHP deployment is the “2012 Baseline.” NREL is the National Renewable Energy Laboratory.

Modeling impacts for geothermal direct-use applications in district heating differed from electric-sector and GHP modeling due to the nature of the technology. In geothermal district heating, underground heat reservoirs are tapped to provide heating for many—sometimes thousands of—buildings. As such, geothermal district-heating systems have community impacts as well as individual impacts that would likely be substantive if such systems were deployed on a national scale. However, limited data and experience constrain understanding of U.S. market potential for geothermal district heating. As such, full market-potential expansion scenarios could not be modeled for geothermal district-heating systems in the *GeoVision* analysis. Instead, the impacts of a limited number of representative systems were quantified, and those results were used to qualitatively describe the impacts that could be realized from expansion based on economic-potential levels. Projected impacts for district-heating systems are discussed in McCabe et al. 2019 and Millstein et al. 2019.

4.4.1 Jobs and Economic Development

The *GeoVision* analysis included assessing geothermal industry employment and economic impacts associated with increased deployment. However, specific job numbers are not reported here because the analysis data are gross numbers only and do not evaluate economy-wide net impacts. The assessment used the National Renewable Energy Laboratory’s Jobs and Economic Development Impact model, commonly known as JEDI.⁹⁵ Details can be found in Millstein et al. 2019.

The majority of jobs in the geothermal electric-power sector depend on the exploration, construction, and deployment of new geothermal installations. As indicated, the employment impacts presented in this



A flow test on a 7,000-foot geothermal well at Naval Air Station Fallon, Nevada. Photo credit: Andrew Tiedeman

chapter represent gross job increases resulting from newly installed capacity in the geothermal electric sector, as opposed to net job impacts in the national economy.⁹⁶ Employment impacts are expressed in terms of cumulative expenditures (Table 4-2).⁹⁷ For the scenarios studied in the *GeoVision* analysis, job increases in the geothermal electric sector are driven primarily by widespread EGS resource potential that could support electricity demand in large population centers.

Job growth in the geothermal electric sector initially reflects industry growth enabled by improvements in regulatory timelines and technologies. The *GeoVision* analysis indicates that around 2030, technology improvements could reduce EGS costs and enable rapid growth in EGS resource deployment. If results of the TI scenario are achieved, EGS deployments would be responsible for the majority of jobs created and increased rates of job growth toward the end of the analyzed period in 2050.

⁹⁵ Information on the JEDI model is available on the National Renewable Energy Laboratory’s website at <https://www.nrel.gov/analysis/jedi/>.

⁹⁶ The *GeoVision* analysis assessed gross job impacts from geothermal deployment compared with BAU scenarios. These gross job impacts represent total jobs needed to fulfill increased geothermal deployment, which may displace other energy generation technologies. The net impacts of this displacement were not calculated in the *GeoVision* analysis; thus, the gross job impacts reported in the *GeoVision* analysis do not represent the impact of geothermal jobs on employment within those other sectors. Assessing such impacts was beyond the scope of the *GeoVision* analysis (Millstein et al. 2019).

⁹⁷ Cumulative expenditures include capital and O&M spending over the analyzed timeframe that is required to support deployment potential modeled in the *GeoVision* analysis.

Table 4-2 contains cumulative expenditures (millions of dollars) on geothermal electric-sector deployment from 2015 to 2050 by state, in the states where geothermal deploys under the TI scenario (Millstein et al. 2019).

State	Cumulative Expenditures (millions of \$)	State	Cumulative Expenditures (millions of \$)
CA	79,851	CO	3,008
WV	27,030	MT	976
OR	26,495	TX	222
ID	21,838	WY	208
NV	17,310	PA	110
UT	14,914	VA	51
AZ	13,754	MS	30
NM	13,339	LA	17
Total (millions of \$) 219,152			

Table 4-2. Cumulative Expenditures on Geothermal Electricity-Generation Capacity Deployment by State in Millions of Dollars (2015–2050) in the TI Scenario

Table Note: Table contains the states in which geothermal deploys in the TI scenario. Cumulative expenditures include capital and operations and maintenance spending required over the analyzed timeframe to support deployment potential modeled in the GeoVision analysis. Expenditures depend on how the model (ReEDS) builds out generation and transmission at a bulk-grid scale. Expenditures in states such as West Virginia, Oregon, and Arizona are driven upward by a complex function of EGS availability, other generation retirements, and demand, levelized by the least-cost generation option. Expenditures shown are absolute values and not relative to the BAU scenario.

The *GeoVision* analysis indicates that, at a local level, geothermal power plants can provide more than double the long-term jobs per powered household when compared to other utility-scale power-generation technologies considered in the *GeoVision* analysis (Figure 4-11) (Millstein et al. 2019, Young et al. 2019). Long-term geothermal jobs are generally operations and maintenance positions filled mainly by local workers (Figure 4-12). As such, wages generated by these jobs are also more likely to be spent locally. Operations and maintenance spending includes royalties, which are unique to geothermal power plants, as well as property taxes, land-lease payments, and other spending.

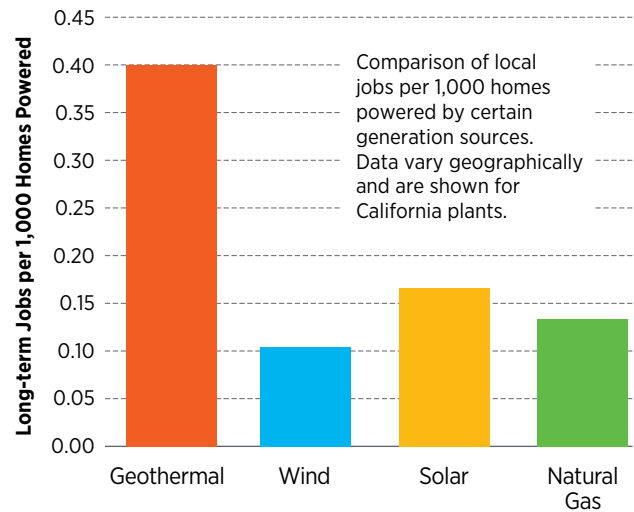


Figure 4-11. Comparison of long-term jobs per 1,000 homes powered, by energy-generation technology

Figure Note: Geothermal can provide more than double the long-term jobs per powered household compared to other electricity-generation technologies considered. As indicated, data shown are for California power plants.

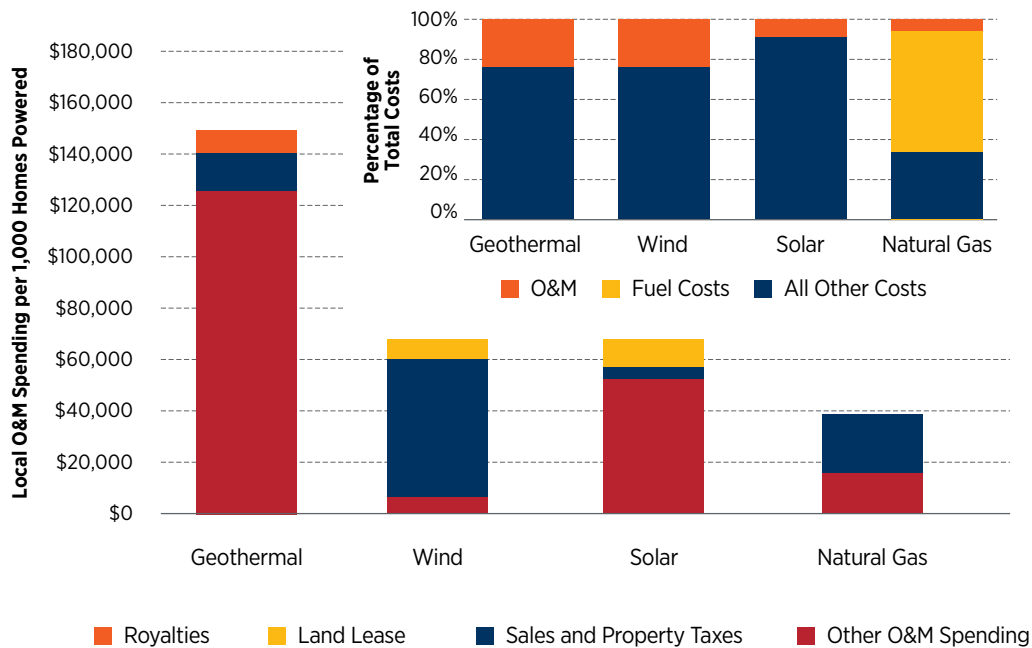


Figure 4-12. Comparison of local operations and maintenance spending per 1,000 homes powered, by energy-generation technology

Figure Note: Data vary geographically and are shown for California power plants.

GHP expenditures can help provide insight on GHP economic impacts and where those impacts might occur. Figure 4-13 illustrates the geographic distributions of gross GHP expenditures in 2030 and 2050 for the BT scenario. Most of the expenditures in 2030 are in Texas and the eastern half of the country. This result is geographically complementary with electric-sector deployment, which occurs mainly in the western United States (Table 4-2). As such, combined

electric-sector and GHP economic impacts would be more geographically diverse when compared to each sector individually. GHP expenditures grow from \$2.9 billion annually in 2030 to \$4.3 billion annually in 2050. From 2030 to 2050, the expenditure increases occur mainly in six states: New Jersey, New York, California, Massachusetts, Michigan, and North Carolina (ranked in order of highest to lowest change).

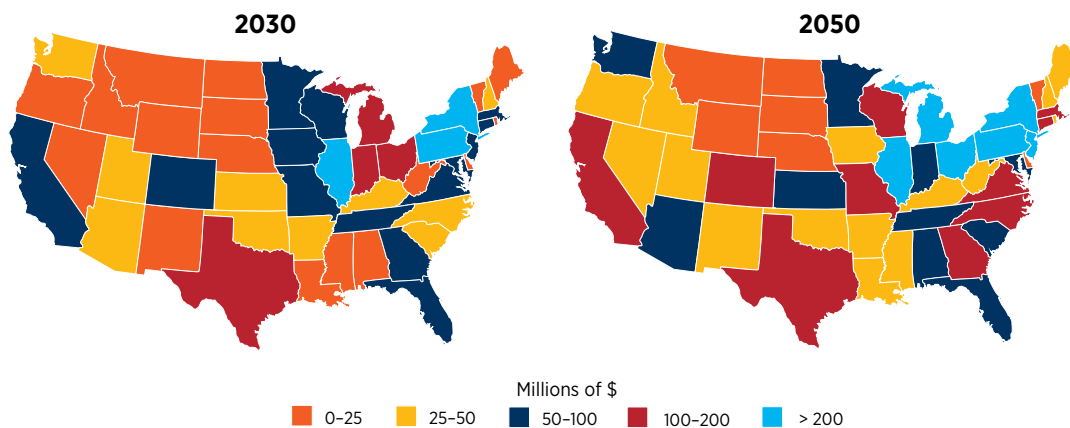


Figure 4-13. Geothermal heat-pump expenditures (in millions of USD) for 2030 (left) and 2050 (right) by state under the Breakthrough scenario

Source: Millstein et al. 2019

Achieving deployment levels identified in the *GeoVision* analysis can increase employment, wages, and economic output in the geothermal electric and non-electric GHP sectors. The analysis also demonstrates that combining geographic trends of development in the geothermal electric and GHP sectors can result in benefits in many U.S. states, particularly the West and Mid-Atlantic regions (Millstein et al. 2019).

4.4.2 Water Use

For the *GeoVision* analysis, water-use impacts were calculated for the electric sector only. This evaluation included two categories of water impacts: 1) water **withdrawal**, which is water removed or diverted from a water source for use, and 2) water **consumption**, which is water evaporated, transpired, or incorporated into products or crops or otherwise removed from the immediate water environment. Water consumption represents a net loss from the local source. For electricity generation, withdrawal is typically water used for cooling and then returned to the source at a slightly elevated temperature, whereas consumption is usually water used for evaporative cooling and not returned directly to the source.

Modeling for water-use impacts focused exclusively on operational water-use requirements, which can vary based on the type of fuel, power plant, and cooling system. Water-use impacts calculated for the *GeoVision* analysis were based on the ReEDS modeling results and extracted directly from the ReEDS model. ReEDS includes water availability in modeling capacity deployment and will restrict deployment of a technology if water resources are not available. Millstein et al. 2019 includes a detailed explanation of the modeling methodology and assumptions for water-use impacts.

Under the *GeoVision* TI scenario, geothermal power generation would represent 8.5% of total national generation in 2050, but only 1.1% of power-sector water withdrawals. Figure 4-14 shows water withdrawals for the TI scenario (Millstein et al. 2019). Because the water-withdrawal percentages for geothermal and other renewable technologies are minor in relative terms, they do not register visibly at full scale in the figure.

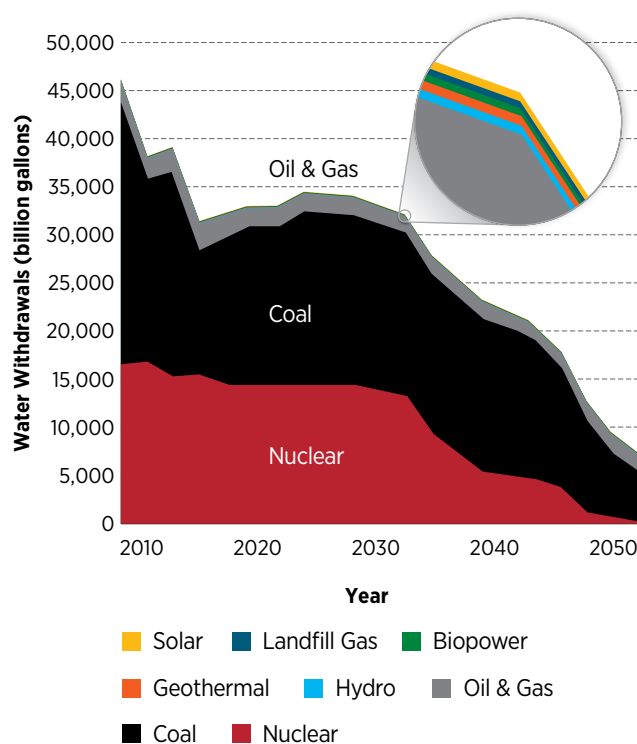


Figure 4-14. Power-sector water-withdrawal impacts in billions of gallons

Source: Millstein et al. 2019

Figure Note: Chart illustrates water-withdrawal impacts from geothermal generation as modeled under the TI scenario. Geothermal, solar, landfill gas, biopower, and hydropower have minimal impact on water withdrawals for the total electric sector; data for these technologies are reflected in the figure but are too small to be seen at full scale. The inset magnifies these data to make them visible.

Under the *GeoVision* analysis Technology Improvement scenario, geothermal energy could represent 8.5% of total national electricity generation while being accountable for only 1.1% of power-sector water withdrawals. The majority of this growth could be supported using non-freshwater sources.

The *GeoVision* analysis indicates that geothermal power generation under the TI scenario impacts water consumption relative to BAU, representing 7.6% of total power-sector water consumption by 2050, as compared to 8.5% of total generation (Figure 4-15). This percentage of water consumption by geothermal power generation represents a cumulative increase from present day to 2050 of about 230 billion gallons systemwide over the BAU scenario—a small

percentage (0.5%) relative to total electric-system-wide consumption (46 trillion gallons cumulatively) over that same time period. Annual water consumption in 2050 in the BAU scenario is about 1.01 trillion gallons, compared with 1.05 trillion gallons under the TI scenario (4% higher). Results are driven by modeling assumptions related to subsurface water loss and the assumed binary, air-cooled configuration for EGS plants (Millstein et al. 2019).

Geothermal technology deployment in the BAU, IRT, and TI scenarios was not restricted on the basis of water quality (i.e., sources being freshwater or non-freshwater). The *GeoVision* analysis evaluated the sensitivity of geothermal growth to restrictions on water sourcing. An alternate sensitivity scenario considered limiting geothermal water use to non-freshwater sources (e.g., brackish groundwater or municipal wastewater). Under the non-freshwater-consumption sensitivity analysis, geothermal deployment could still increase to nearly the same levels as in the freshwater scenario, maintaining about 90% of total projected deployment. The sensitivity analysis results indicate the potential to support almost all of the geothermal energy growth using only non-freshwater resources. This means that geothermal deployment growth could be supported even where access to freshwater is limited. Achieving the deployment results of the *GeoVision* analysis is not expected to materially impact the water needs of the wider electric system.

4.4.3 Air Emissions

The *GeoVision* analysis assessed the impact of increased geothermal deployment on air emissions, including greenhouse gas (GHG) emissions, measured as carbon-dioxide equivalents (CO₂e),⁹⁸ as well as sulfur dioxide (SO₂), nitrogen oxides (NO_x), and fine particulate matter (PM_{2.5}).⁹⁹ Results of the analysis indicate opportunities for reduced emissions and improved U.S. air quality resulting from greater geothermal deployment in both the electric and non-electric sectors.

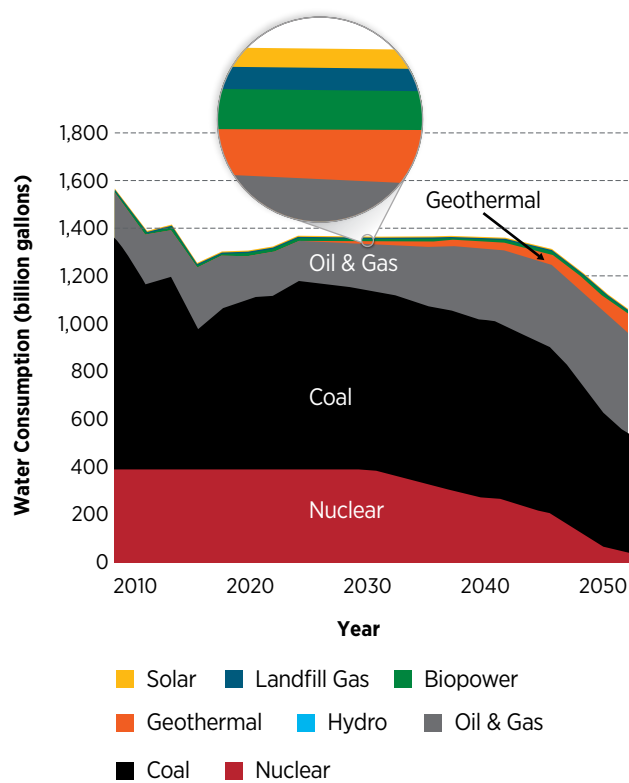


Figure 4-15. Water-consumption impacts from the geothermal power sector (in billions of gallons) under the Technology Improvement scenario

Source: Millstein et al. 2019

Figure Note: Water consumption increases with increasing geothermal power generation, accounting for 7.6% of total power-sector water consumption by 2050 and 8.5% of total generation. Comparatively, however, geothermal accounts for a fraction of the water consumption of coal, natural gas, and nuclear power generation. Solar, landfill gas, biopower, and hydropower are included in systemwide data but represent consumption values that are too low to see at full scale in the figure. The inset magnifies these data to make them visible.

Figure 4-16 illustrates annual life cycle greenhouse gas emissions and annual displaced life cycle greenhouse gas emissions in the entire electric sector under the BAU, IRT, and TI scenarios. In the entire electric sector, geothermal deployment under the TI scenario—particularly from EGS resources—reduces total sector CO₂e emissions by a cumulative 516 million metric tons (MMT) from 2015 to 2050, on a life cycle basis relative to a BAU scenario. By the end of the analyzed period (2050), the GHG emissions avoided annually are roughly equal to the annual GHG emissions of 6.4 million cars.¹⁰⁰

⁹⁸ Carbon-dioxide equivalents are a summation of the GHG effects of contributing gases (e.g., methane) measured on a carbon-dioxide equivalency basis.

⁹⁹ PM_{2.5} refers to fine inhalable particulates that are 2.5 microns or less in diameter.

¹⁰⁰ Car-emission equivalent calculations assume that a typical U.S. passenger vehicle emits about 4.7 metric tons of CO₂ per year, based on fuel economy of about 21.6 miles per gallon and 11,400 miles of travel per year (Environmental Protection Agency 2014).

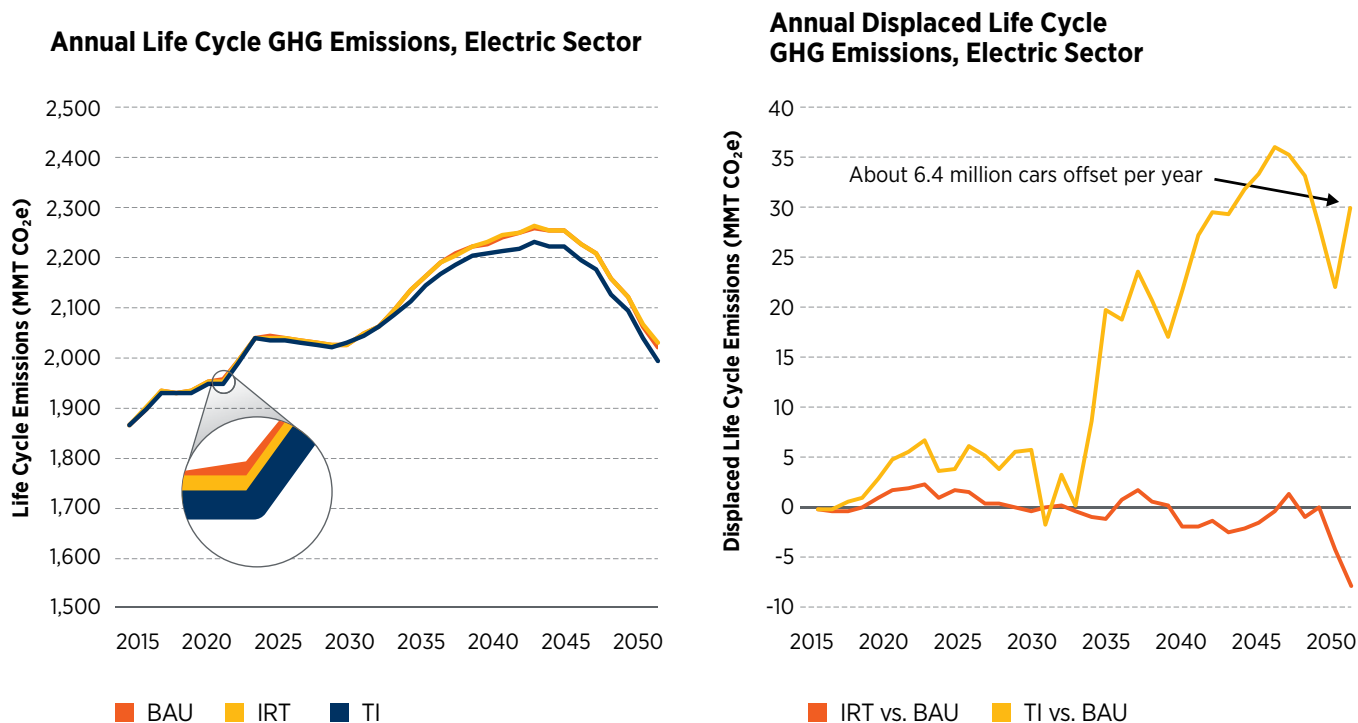


Figure 4-16. Annual life cycle greenhouse gas emissions (left) and annual displaced life cycle greenhouse gas emissions (right) in the entire electric sector under the Improved Regulatory Timeline, Technology Improvement, and Business-as-Usual scenarios

Source: Millstein et al. 2019

Figure Note: For the TI scenario, geothermal deployment in the electric sector results in a cumulative total reduction of 516 MMT of CO₂e from 2015 to 2050, on a life cycle basis relative to a BAU scenario. By the end of the analyzed period, the annual avoided emissions are equivalent to the emissions from about 6.4 million cars. “MMT CO₂e” is million metric tons of CO₂e. Negative impacts (i.e., minor increases in emissions resulting in negative displacement) derive from increases in systemwide emissions, not from geothermal power plants specifically.

Figure 4-17 illustrates annual life cycle greenhouse gas emissions and annual displaced life cycle greenhouse gas emissions in the heating and cooling sector under the BAU and BT scenarios, relative to the 2012 baseline. In the heating and cooling sector, deployment of GHPs in the BT scenario results in as much as ~90 MMT of displaced annual GHG emissions by 2050 relative to the 2012 GHP baseline—the equivalent emissions of about 20 million cars. Given the nature of GHP deployment, GHG emissions reductions from the technology are distributed relatively evenly throughout the contiguous United States, with somewhat higher amounts in the Mid-Atlantic, Midwest, and Great Lakes regions (Millstein et al. 2019).

Assuming the most aggressive technology improvements modeled for both the electric and non-electric sectors, the overall results of the *GeoVision* analysis of air-emissions impacts indicate that—by 2050—geothermal deployment could avoid annual GHG emissions equivalent to removing a total of about 26 million cars from U.S. roads relative to the 2012 baseline. As noted, geothermal deployment in the U.S. electric sector, as modeled in the TI scenario, yields *cumulative* life cycle GHG emissions reductions of 516 MMT of CO₂e through 2050 relative to BAU, whereas GHP deployment in the heating and cooling sector yields *cumulative* life cycle GHG emissions reductions of 1,281 MMT of CO₂e through 2050 relative to the 2012 baseline. Across both the electric and heating and cooling sectors under the most aggressive

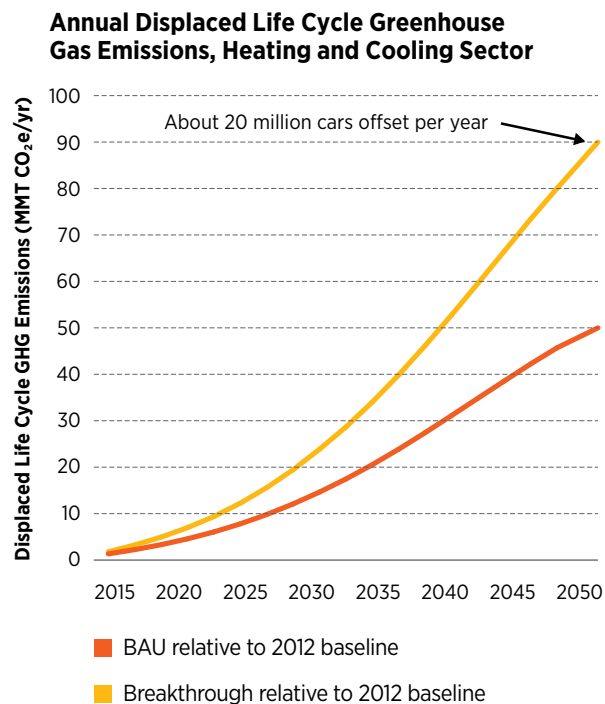
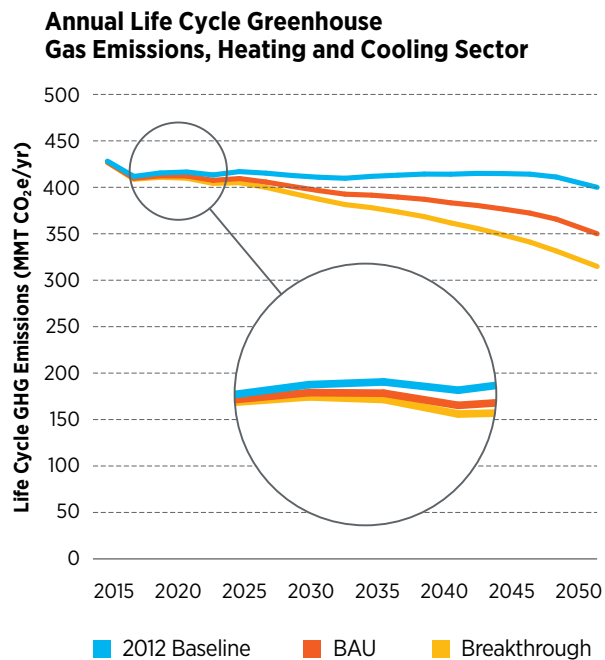


Figure 4-17. Annual life cycle emissions (left) and annual displaced life cycle greenhouse gas emissions (right) in the entire heating and cooling sector under the Breakthrough and Business-as-Usual scenarios, relative to the 2012 GHP baseline

Source: Millstein et al. 2019

technology improvement and growth scenarios, the rate of annual GHG emissions reductions increases through 2050, reaching a combined *annual* reduction of 117 MMT CO₂e by 2050 (Millstein et al. 2019).

Results in the *GeoVision* analysis for SO₂, NO_x, and PM_{2.5} emissions also demonstrate improvements in air quality resulting from increased deployment of geothermal technologies. Figure 4-18 illustrates total electric-sector emissions for SO₂, NO_x, and PM_{2.5} and net air-quality impacts (in thousands of metric tons) resulting from the *GeoVision* scenarios compared to the BAU scenario. As with GHG emissions, improvements in SO₂ and NO_x are especially notable for the TI scenario in the electric sector. As illustrated in Figure 4-18, the TI scenario results in greater reductions in SO₂, NO_x, and PM_{2.5} emissions than the IRT scenario. Achieving the TI scenario reduces cumulative emissions of SO₂, NO_x, and PM_{2.5} by 279,000, 417,000, and 54,000 metric tons,

By 2050, geothermal deployment in the nation's electric and non-electric sectors could reduce greenhouse gas emissions equivalent to removing 26 million cars from U.S. roads annually.

respectively, relative to the BAU scenario. These reductions represent about 1% of total emissions in each category and are concentrated in the time period between 2030 and 2050. Reductions of emissions of SO₂, NO_x, and PM_{2.5} are seen in all modeled regions of the country, but are highest in Texas and the southwestern region of the United States. If the nation achieves the large-scale deployment of EGS resources identified in the *GeoVision* analysis TI scenario, then these air-quality benefits are expected to increase around 2030.

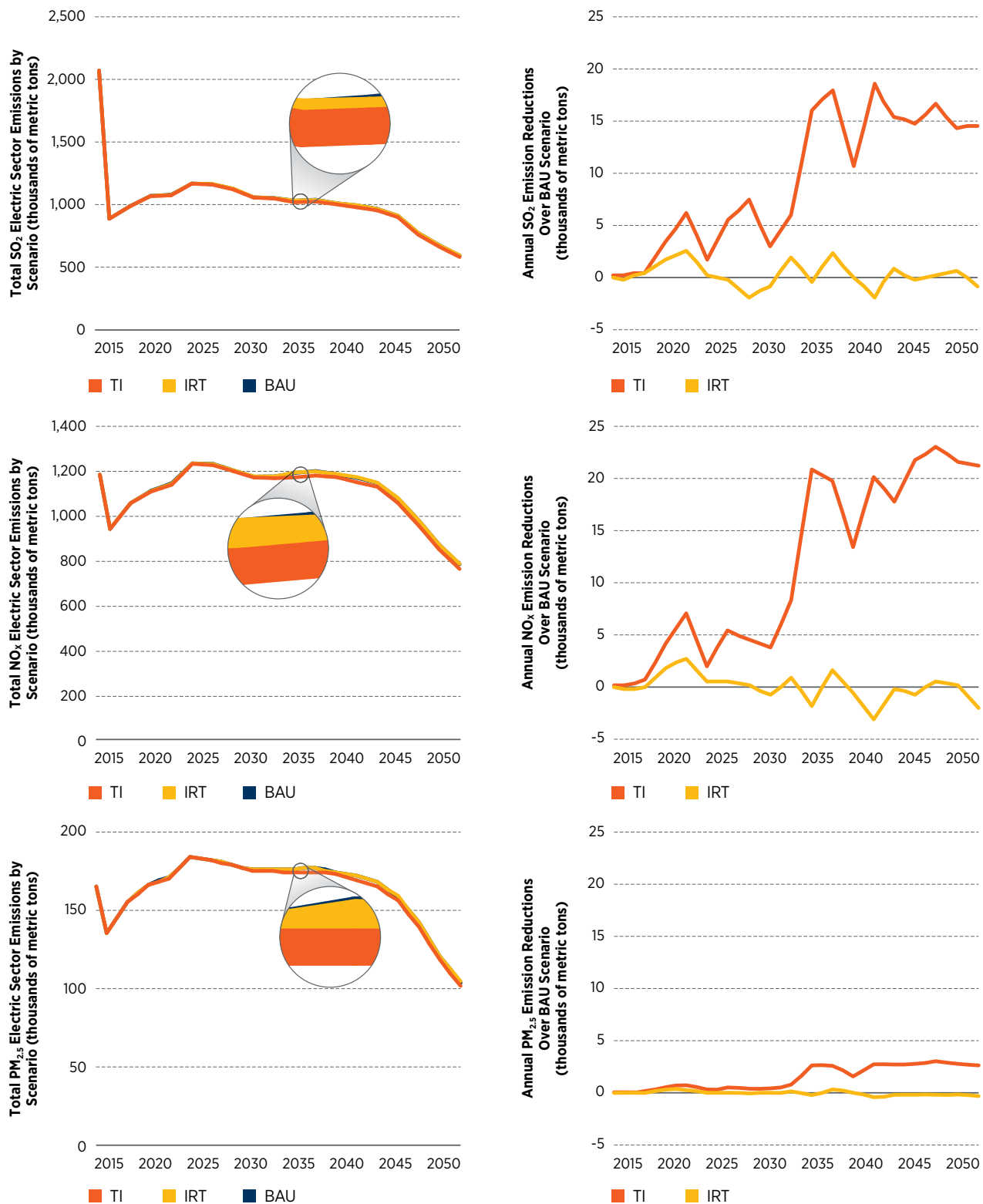


Figure 4-18. Air-quality impacts (SO₂, NO_x, and PM_{2.5} emissions) for the entire electric sector, illustrating total (left) electric-sector emissions and annual (right) emissions reductions impacts from the GeoVision scenarios on electric-sector emissions (in thousands of metric tons)

Source: Millstein et al. 2019

Figure Note: Emissions reductions (right) are reported in thousands of metric tons of NO_x, SO₂, or PM_{2.5} emissions removed from the electric sector and attributable to geothermal deployment. The highest emissions reductions in the electric sector result from the TI scenario. Reductions begin in about 2030, when large-scale deployment of EGS resources occurs. Negative impacts (i.e., minor increases in emissions) derive from increases in systemwide emissions, not from geothermal power plants specifically.

In the heating and cooling sector, the decrease in on-site fuel use that results from achieving the BT scenario reduces cumulative emissions (from 2015 to 2050) of SO₂, NO_x, and PM_{2.5} by 232,000, 711,000, and 57,000 metric tons, respectively, relative to the 2012 baseline. These emission reductions are equivalent to double to triple the total single-year SO₂ and NO_x emissions from all residential combustion sources and one-fifth of a single year of PM_{2.5} residential emissions (Environmental Protection Agency 2016). Figure 4-19 illustrates the total GHP heating and cooling sector emissions for SO₂, NO_x, and PM_{2.5} and net air-quality impacts (in thousands of metric tons) resulting from the *GeoVision* BAU and BT scenarios, compared to the 2012 GHP baseline. The emission reductions increase gradually over time. In the case of GHPs, significant benefits are found even in the BAU scenario, with the additional deployment in the BT scenario providing further benefits.

Further details about air-emissions impacts, including a description of methodologies and models, are provided in Millstein et al. 2019.



An evaporative cooling tower at Socrates Geothermal Power Plant (The Geysers, California). Photo credit: Geothermal Resources Council

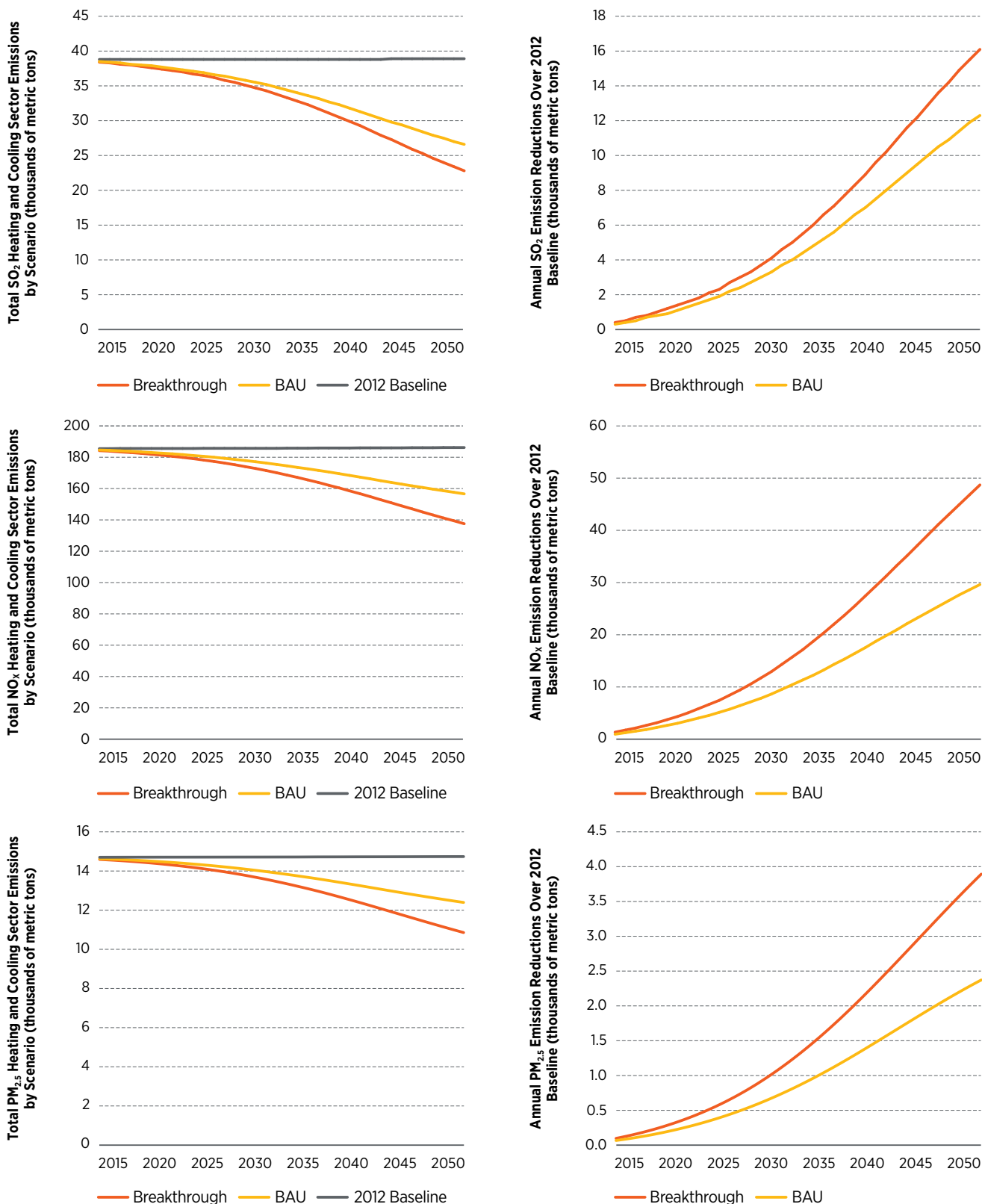


Figure 4-19. Air-quality impacts for the heating and cooling sector, illustrating total sector emissions of SO₂, NO_x, and PM_{2.5} and annual emissions reductions impacts (in thousands of metric tons) from the *GeoVision* scenarios on heating and cooling sector emissions

Source: Millstein et al. 2019

Figure Note: Air-quality impacts reflect reductions (right) in cumulative NO_x, SO₂, or PM_{2.5} emissions resulting from reduced on-site fuel use under the BAU and BT scenarios. These emissions reductions track GHP capacity deployment values and increase gradually over time. "2012 Baseline" refers to the 2012 installed GHP baseline used in the analysis.



CHAPTER FIVE

The *GeoVision* Roadmap: A Pathway Forward

Monitoring geothermal fumarolic activity on Akutan Island, Alaska.

Photo credit: Nick Hinz

5 The *GeoVision* Roadmap: A Pathway Forward

The *GeoVision* analysis supports the conclusions that extensive geothermal energy deployment by 2050 is feasible and that increased deployment of geothermal energy could provide broad, direct benefits to the United States. These benefits include reliable and renewable “always-on” power generation with load-following capabilities; cost-effective, energy-efficient heating and cooling solutions for residential and commercial buildings; economic benefits to the geothermal industry; and environmental benefits for the nation. As discussed in Chapter 2, however, realizing the opportunities offered by geothermal resources will require overcoming a range of technical and non-technical barriers aimed at reducing the risks and costs of geothermal development.

This chapter presents the *GeoVision* Roadmap: a compilation of technical, economic, and institutional actions across the geothermal community—including the U.S. Department of Energy (DOE), industry, academia, and other stakeholder groups—that can help address barriers and ensure the continued contribution of geothermal energy as a renewable and diverse energy solution for the United States. The Roadmap is not intended to be an exhaustive list; it is instead meant to serve as a guide that the collective geothermal community can use to meet those key objectives and allow the nation to harness the potential offered by geothermal resources.

The Roadmap actions in this chapter aim to achieve the possible and potential deployment levels indicated by the *GeoVision* analysis. The actions address steps to advance both proven and unproven technologies. For *proven* technologies, technical advancements will help, but the most vital steps needed are to overcome barriers related to project financing, regulatory timelines, outreach and education, and market structures. For *unproven* and developing technologies, the most crucial steps are research and development (R&D) and technology advancement.

The *GeoVision* Roadmap is a compilation of technical, economic, and institutional actions across the geothermal community that can help address barriers and ensure the continued contribution of geothermal energy as a renewable, reliable, and diverse energy solution for the United States.

The Roadmap actions also address the three key principles or foundational objectives of the *GeoVision* analysis, as introduced in Section 1.2. This relationship is discussed in more detail in Section 5.2.

5.1 Risks of Inaction

Geothermal energy provides reliable electricity generation, with capabilities to meet grid flexibility and load-following requirements, and it serves heating and cooling needs. This energy underlies the entire country, is “always-on,” and represents vast domestic potential. The *GeoVision* analysis outlines the potential for geothermal energy through 2050 and identifies economic benefits to the geothermal industry and environmental benefits to the United States that can result from increased geothermal deployment (Chapter 4). However, only a fraction of the nation’s geothermal energy potential has been realized, due to a combination of technical and non-technical barriers that constrain the use of this abundant, domestic energy resource.

An important question is: What are the repercussions for the nation if challenges to increased geothermal deployment are not addressed?

Electric Sector:

The *GeoVision* analysis confirms the potential for geothermal deployment of more than 60 gigawatts-electric (GW_e) in the electric sector. Getting

to even modest levels of deployment, however, depends on reducing geothermal development timelines by optimizing regulatory processes and improving the discovery of undiscovered hydrothermal resources through better resource assessment and exploration technologies. The explosive growth potential to 60 GW_e indicated by the Technology Improvement scenario in the *GeoVision* analysis is also contingent on developing innovative technologies to create reliable, sustainable, and cost-effective enhanced geothermal systems (EGS). Without the expanded and accelerated exploration and innovative technologies supported by actions in this *GeoVision* Roadmap, the geothermal electric sector is likely to continue to grow at a rate of only ~2% per year (Augustine et al. 2019), resulting in deployment of about 6 GW_e by 2050 (Business-as-Usual scenario). This limited deployment would prevent the United States from realizing the contributions that geothermal energy can make to the nation's electricity sector, including efficiency, reliability, and resiliency.

Non-Electric Sector:

As a cost-effective and efficient source of reliable heating and cooling, geothermal heat pumps (GHPs) can play a major role in the residential and commercial sectors. Growth in the GHP market, however, will require better consumer awareness and improved financing options, as well as technology advances that can lower the costs and improve the efficiencies of heat pumps and ground heat-exchange loops. EGS technology advancements will also be essential to lower costs and facilitate expansive increases in deployment potential for district-heating systems and other direct-use applications. Failure to overcome these challenges would mean missed opportunities to supply the country with renewable heating and cooling of residential and commercial buildings, in addition to missed opportunities for meeting the heat energy demands of a wide variety of industries and commercial enterprises.

5.2 The Roadmap Approach

The *GeoVision* Roadmap builds on the findings of the *GeoVision* analysis, which examines the potential of geothermal energy across multiple market sectors. The actions discussed in the Roadmap are intended to stimulate broadly inclusive, multistakeholder engagement to advance geothermal energy. The potential pathways resulted from a collaborative

effort led by DOE, with contributions from national laboratories, a set of 20 industry peers known as "Visionaries," and a diverse group of 34 expert reviewers representing a range of geothermal stakeholders (Appendix D).

The Roadmap is not intended to be prescriptive; it does not specify how or by whom suggested actions should be accomplished. The intent is to begin an evolving, collaborative, and necessarily dynamic process to inform future action across industry, government, academia, and other geothermal stakeholders.

As explained in Chapter 3 and Appendix C, geothermal development potential is highly sensitive to cost, and advancing the industry depends on the extent to which costs can be lowered through collective stakeholder engagement and efforts. For this reason, many of the Roadmap actions focus on areas related to cost: reduced development timelines, which can improve project economics; improved technologies that can more reliably explore for and target wells; and improved technologies that can reduce well-drilling costs and improve well productivity through novel stimulation techniques.

The Roadmap is not intended to be prescriptive; it does not specify how or by whom suggested actions should be accomplished. Furthermore, it is beyond the scope of the *GeoVision* analysis to propose unintroduced policies or policy changes, and the analysis does not do so. The analysis considers only policies that are in force or that have been introduced but not enacted. The intent is to begin an evolving, collaborative, and dynamic process to inform future action across industry, government, academia, and other geothermal stakeholders. Several action areas will include collaboration among federal, state, and local agencies, particularly where land-management negotiations are essential to a successful outcome.

As noted, the *GeoVision* analysis was based on three key objectives: 1) to increase access to geothermal resources, 2) to reduce costs and improve economics for geothermal projects, and 3) to improve education

and outreach about geothermal energy through stakeholder collaboration. The three objectives align with the overarching goal of harnessing the potential of geothermal energy to increase value for the nation. The Roadmap targets these three key objectives through four major Action Areas, each with several key actions and sub-actions in which geothermal stakeholders can engage:

Action Area 1: Research Related to Resource Assessments, Improved Site Characterization, and Key Technology Advancements

Action Area 2: Regulatory Process Optimization

Action Area 3: Maximizing the Full Value of Geothermal Energy

Action Area 4: Improved Stakeholder Collaboration

The complex, many-to-many relationships between the key objectives and the Action Areas are reflected in the interrelated nature of the Roadmap. For example, technology advances discussed in Action Area 1 and regulatory process optimizations from Action Area 2 will impact access to resources and reductions in cost, whereas improved valuation for geothermal energy in Action Area 3 affects costs as well as education and outreach. Domestic and international collaboration (Action Area 4), especially on unproven and developing technologies, will impact the speed with which those technologies advance, thus driving resource access, costs, and global interest in geothermal energy. The interrelationships across the three key objectives and four Action Areas are the foundational framework of the Roadmap.

The Roadmap is intended to be a living document that will be modified using an evolving and collaborative process; it thus includes an action suggesting periodic reviews of progress toward the objectives. The reviews will allow stakeholders to assess the impacts of the Roadmap and suggest adjustments as necessary and appropriate through 2050. Regular reviews will allow for optimal adaptation to changing technologies, markets, public priorities, and policy factors. They will

also support the ongoing prioritization of potential pathways to attain shared objectives across stakeholder groups.

5.3 The *GeoVision* Roadmap

Table 5-1 summarizes the *GeoVision* Roadmap, including the Action Areas and related primary suggested actions. The subsequent sections include a broad explanation for each Action Area and its related key actions and sub-actions. The order of the Roadmap actions is not intended to imply priority or relative importance. As previously noted, the Roadmap is meant to be a living document that will rely on stakeholder input to evolve and accommodate continued growth in geothermal deployment.



Autumn colors at Pilgrim Hot Springs on the Seward Peninsula in Alaska. Photo credit: Dick Benoit

Action Area 1: Research Related to Resource Assessments, Improved Site Characterization, and Key Technology Advancements

Key Action 1.1 – Conduct national- and local-scale resolution resource assessments across the geothermal resource spectrum

Key Action 1.2 – Improve detection of subsurface signals

Key Action 1.3 – Improve geothermal drilling and wellbore integrity

Key Action 1.4 – Improve geothermal energy resource recovery

Key Action 1.5 – Improve geothermal resource and asset monitoring, modeling, and management

Action Area 2: Regulatory Process Optimization

Key Action 2.1 – Improve land access

Key Action 2.2 – Improve the ability to develop geothermal energy in accessible lands

Key Action 2.3 – Evaluate geothermal heat-pump regulatory processes

Action Area 3: Maximizing the Full Value of Geothermal Energy

Key Action 3.1 – Improve valuation of and compensation for geothermal energy

Key Action 3.2 – Investigate geothermal hybrid opportunities

Key Action 3.3 – Quantify additional geothermal value streams

Key Action 3.4 – Assess the economic barriers and solutions pertaining to direct-use applications and geothermal heat pumps

Key Action 3.5 – Identify opportunities to improve standards, business models, and economics for direct-use applications and geothermal heat pumps

Action Area 4: Improved Stakeholder Collaboration

Key Action 4.1 – Maintain the Roadmap as a vibrant, active process

Key Action 4.2 – Improve public education and outreach about geothermal energy

Key Action 4.3 – Increase awareness of employment and training opportunities across all geothermal energy technologies

Table 5-1. *GeoVision* Roadmap Summary

Action Area 1: Research Related to Resource Assessments, Improved Site Characterization, and Key Technology Advancements

The actions outlined in Action Area 1 aim at understanding where geothermal resources exist as well as increasing access to and optimizing use of those resources. These objectives will be achieved by improving resource assessments, advancing technology, and improving efficiency. Results of these actions include better and more widespread opportunities for domestic geothermal resource use as well as reduced development cost through improved technologies and lower risk. Success will require increased collaboration among the global geothermal industry and its stakeholders. Outreach to other energy sectors will also contribute to achieving these actions.

Geothermal resources are unique among renewable energy technologies in that significant exploration and capital expenditure are required to locate, characterize, and prove a resource. Wind, solar, and hydropower resources are already well characterized, whereas the majority of hydrothermal resources are still undiscovered and—as such—uncharacterized. National assessments are available for EGS resources, but not at a resolution that can support practical investments in development. Similarly, GHP resources lack a central database of properties that indicate GHP suitability, such as a national map of soil thermal conductivity at the appropriate resolution. Improved resource and site characterization are key for increasing geothermal deployment in both the electric and non-electric sectors.

Harnessing geothermal resources at the scale envisioned by the *GeoVision* analysis will require improving and advancing technology. Progress is needed in detecting subsurface signals to remotely identify and characterize underground attributes. Similar to the way the medical field uses radiology to assess the need for and improve the success rates of more costly and invasive procedures, the geothermal industry would benefit from technology breakthroughs in non-invasive, lower-cost geophysical and remote-sensing technologies. Once geothermal resources are identified and characterized at a level that justifies a more capital-intensive investment toward development, technology advances in drilling and



Old Faithful Geyser in Yellowstone National Park, Wyoming.
Photo credit: Jim Stimac

wellbore integrity will play a critical role in lowering the costs of development. Major advances in reservoir and subsurface engineering will be required to enable the cost-effective creation of EGS reservoirs and sustain their productivity once they are created.

Enhanced and innovative tools and techniques can also ensure optimal resource use, improve well life cycles, and enhance overall performance of geothermal wells. These results can, in turn, reduce risk and costs for geothermal developers and minimize adverse environmental impacts. Technology advances are crucial for developing commercially competitive EGS projects and unlocking the full potential of U.S. geothermal resources in the electricity and district heating and cooling sectors. New geothermal technologies should also leverage existing innovations from other U.S.

industries, including oil and gas. At the same time, investments in geothermal technology advancements are likely to yield benefit back to the oil and gas industry—e.g., the geothermal industry’s DOE-supported development of polycrystalline drill bits and the subsequent adoption of this technology across the global oil and gas industry (Text Box 1-1).

Once geothermal resources are located, characterized, and harnessed, long-term production of geothermal energy will rely on improved resource monitoring, modeling, and management. Achieving these objectives can improve decision making and ensure longer life and better management of reservoirs and resources.

The DOE’s 2019 Frontier Observatory for Research in Geothermal Energy (FORGE) Roadmap (McKittrick et al. 2019) includes activities that are synergistic with and cross-cut several key actions and sub-actions in Action Area 1. The FORGE Roadmap focuses on critical research areas in fracture control, reservoir management, and stimulation. These activities are applied specifically to technology advancements for EGS and are intended to be implemented at the DOE FORGE site in Milford, Utah. The *GeoVision* Roadmap highlights other activities that can be implemented by various stakeholder groups to address additional research areas and opportunities.



Drilling a geothermal well at twilight at McGinness Hills, Nevada.

Photo credit: Piyush Bakane

KEY ACTION 1.1 – Conduct national- and local-scale resolution resource assessments across the geothermal resource spectrum

Improving, expanding, and building on past assessments of geothermal resources by state and federal agencies and expanding assessments to include resources for GHP applications can help identify market opportunities.

DELIVERABLE(S): Geothermal resource assessments that quantify electric and non-electric opportunities at the national and local scales.

IMPACT(S): Better understanding of the location and diversity of geothermal resources, resulting in increased developer interest and reduced development costs and risk.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 1.1.1: Conduct assessments of U.S. geothermal resource potential.	High-resolution maps at various scales indicating key subsurface parameters for both electric and non-electric sector resources.	Reduced exploration risk and costs. Additional identified and developable resources.

Rationale for Actions

SUB-ACTION 1.1.1: Conduct assessments of U.S. geothermal resource potential.

The economic viability of developing a geothermal resource is a complex function of geological and subsurface characteristics, combined with surface and subsurface access to those resources, market and transmission constraints, and wider stakeholder support. Variables such as market, transmission, and stakeholder support for a project cannot be determined without first understanding the resource potential—that is, where is the resource and what is its grade or quality? As such, the resulting economic determinations are only as accurate as the quality of the resource assessment data on which they are based. Mitigating uncertainty in resource assessments lowers the risk of unproductive exploration, thus reducing development costs.

The U.S. Geological Survey and the National Renewable Energy Laboratory developed national-scale assessments of conventional hydrothermal resources and EGS resources. The U.S. Geological Survey estimates more than 30 GW_e of undiscovered conventional hydrothermal resource potential in the United States (Williams et al. 2008), and the National Renewable Energy Laboratory (Augustine 2016)

estimates more than 5,000 GW_e of EGS potential at depths between 3 and 7 kilometers (about 2 to 4 miles) across the country. Improving the quantity and spatial resolution of national-scale assessment data will reduce uncertainty and can potentially identify more resources (in terms of quantity and geographic distribution) than estimated as of 2017. As an example, the *GeoVision* analysis considered sensitivity runs comparing regional, high-resolution EGS resource assessments with broader national-scale data assessments based on EGS resource data from Southern Methodist University. The result was the identification of more than 84 GW_e of additional resources in the Great Basin area alone (Augustine et al. 2019).

High-resolution data on key soil properties for sizing ground heat exchangers and evaluating GHP economics (thermal conductivity and heat capacity) have not been compiled with sufficient resolution at a national scale. Improving the collection, availability, and integration of such data at the national and regional levels will improve economic and market-potential assessments for GHPs. Doing so will also improve the ability of developers to appropriately size and engineer GHP systems to improve efficiency and to reduce system and installation costs.

KEY ACTION 1.2 – Improve detection of subsurface signals

Enhancing exploration tools for more reliable and accurate detection of geothermal reservoirs at depth can reduce development costs and create additional geothermal development opportunities.

DELIVERABLE(S): Tools and technologies that provide greater understanding of subsurface characteristics vital to geothermal development, including temperature, permeability, and chemistry.

IMPACT(S): Reduced uncertainty and development costs. Improved discovery of geothermal resources.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 1.2.1: Develop exploration tools that identify undiscovered resources and improve the ability to identify prospective enhanced geothermal system resources.	Innovative exploration tools and methods. Big-data integration of multidisciplinary technical information.	Improved identification, increased rate of discovery, and increased deployment of undiscovered and deep enhanced geothermal system resources. Improved project economics and reduced exploration and development costs.
SUB-ACTION 1.2.2: Improve resolution of existing geophysical methods.	Improved resource characterization through geophysical tools, techniques, and methodologies. Improved data collection and evaluation methods.	Reduced exploration cost and risk. Increased geothermal deployment.

*Rationale for Actions***SUB-ACTION 1.2.1: Develop exploration tools that identify undiscovered resources and improve the ability to identify prospective enhanced geothermal system resources.**

New exploration tools are needed to find additional geothermal resources. Most of the identified hydrothermal systems in the United States are associated with surface expressions of thermal features (e.g., geysers, hot springs, fumaroles) that indicate a potential geothermal resource at depth. In contrast, most undiscovered resources do not display these physical manifestations and are therefore difficult to identify using existing industry exploration techniques. Expensive and invasive drilling is the only way to confirm the existence of a geothermal resource. One of the most effective ways to reduce geothermal development costs is to avoid drilling non-productive wells. Improving the ability to identify prospective geothermal resources and target wells into those resources will lower the risk of drilling unnecessary wells. Improving drilling success rates will also impact overall investor confidence in geothermal developments, which will, in turn, reduce project financing costs.

The development and availability of improved exploration tools that can reliably identify geothermal resources in part underpin the *GeoVision* analysis Technology Improvement (TI) scenario (Chapter 3). Technology improvements can reduce the costs of exploration drilling and full-size confirmation wells, and can improve drilling success rates. In the TI scenario, the effects of such improvements on both conventional hydrothermal and EGS are lower capital costs of development and improved favorability for geothermal project economics.

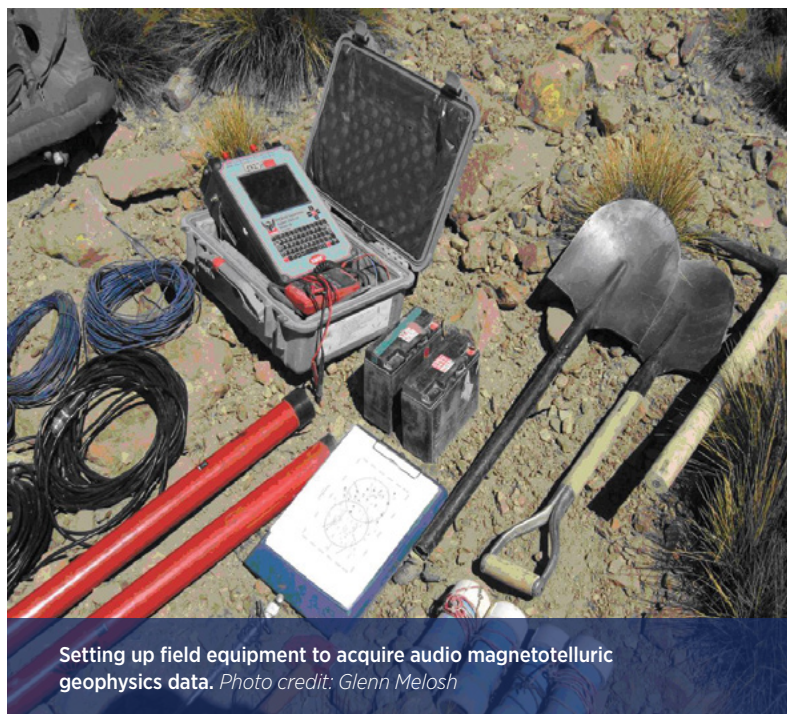
New and innovative exploration technologies and capabilities are needed to characterize subsurface permeability, temperature, and chemistry, along with major geologic structures and stress states in areas where no surface expression exists. Innovative technologies will be the primary means by which additional conventional and EGS resource potential can be identified and captured. Existing exploration tools would benefit from improvements in geophysical, geochemical, and geological sampling, modeling, analysis, and remote sensing. The geothermal industry would also benefit from the ability to integrate multidisciplinary datasets and new methodologies for

capturing value from such data. In particular, advances in the field of machine learning could produce new capabilities for characterizing the subsurface through automated pattern identification and data interpretation tasks. Many of these technologies and capabilities are in early stages of research and development.

SUB-ACTION 1.2.2: Improve resolution of existing geophysical methods.

Improving existing geophysical methods and resolution will increase resource discovery and well targeting for both conventional hydrothermal and EGS resources. Seismic-reflection techniques and data-reduction algorithms used by other industries have not been as effective in the hard-rock environments where permeability is fracture-dominated—environments commonly encountered in geothermal energy systems. The most successful geophysical tools to date for imaging geothermal reservoirs in hydrothermal settings use geophysical resistivity methods; however, resolution of these imaging techniques is currently insufficient to identify and target discrete, fracture-hosted permeability. Effort should be directed toward improving existing resistivity-based geophysical methods; enhancing application of seismic reflection to geothermal environments; and developing innovative geophysical technologies and methods that show

promise for identifying, imaging, and targeting permeability in geothermal settings. For EGS, geophysical advances in areas such as passive seismic monitoring, gravity and magnetic analysis, and joint inversion of datasets will improve real-time understanding of stimulations and reservoir evolution, allowing developers to create larger, more productive reservoirs.



Setting up field equipment to acquire audio magnetotelluric geophysics data. Photo credit: Glenn Melosh

KEY ACTION 1.3 – Improve geothermal drilling and wellbore integrity

Integrating improved drilling and well-completion technology, better well design and construction materials, improved decision making, and innovative drilling financing can help industry realize better drilling efficiencies and effectiveness.

DELIVERABLE(S): New designs and approaches that enhance drilling efficiency and reduce well costs.

IMPACT(S): Reduced costs and risks, and improved reliability.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 1.3.1: Develop drilling data repository.	A centralized, industry-wide repository of drilling information. A published set of standardized industry data-collection practices.	Improved overall drilling processes and better probability of drilling success.
SUB-ACTION 1.3.2: Increase technology and tool transfer from the oil and gas industry.	Catalog of existing oil and gas technologies that could improve geothermal drilling and lower cost barriers. Creative financing and incentive structures to facilitate technology transfer.	Improved drilling success rates and reduced costs. Improved geothermal project financing.
SUB-ACTION 1.3.3: Develop new drilling technologies, methods, and tools specific to geothermal environments.	New and improved drilling tools, technologies, and techniques, accompanied by standardized operating procedures for geothermal environments.	Better drilling success rates and reduced costs. Improved geothermal project financing. Faster construction timelines and increased development.
SUB-ACTION 1.3.4: Improve drilling decision making, operational culture, and efficiency.	Industry-wide studies of organizational and management culture impacts on effective team decision making. Guidance for implementing culture changes and disseminating industry best practices.	Reduced learning curves for drilling. Improved probability of success and lower drilling costs. Better organizational decisions and improved health and safety across geothermal projects.
SUB-ACTION 1.3.5: Improve well life cycles.	New and improved well design and engineering approaches. New monitoring and assessment capabilities and techniques.	Increased well life cycles. Improved project financing and operational economics.

Rationale for Actions

SUB-ACTION 1.3.1: Develop drilling data repository.

The global oil and gas and mining industries drill tens of thousands of wells per year, in environments with relatively distinct and consistent classes of geological conditions. Collecting and analyzing large sets of drilling data has allowed these industries to optimize drilling approaches for specific conditions and subsurface environments, which has resulted in faster, lower-cost, and lower-risk drilling.

By comparison, the geothermal industry drills far fewer wells and does so through more variable rock types; as such, data on geothermal drilling are scarce by comparison. Drilling costs can account for 50% or more of the total capital costs for a geothermal energy project, which makes reducing drilling costs one of the most important factors for geothermal energy production to become economically viable across a range of subsurface environments (Lowry et al. 2017). The geothermal industry could benefit from using approaches similar to those used in mining and oil and gas to compile a critical mass of information and

data to optimize drilling. Step-change improvements in geothermal drilling could be supported by two key activities: 1) a collaborative international effort to share data and knowledge through a well-managed drilling data repository, potentially integrated with the National Geothermal Data System; and 2) early-stage R&D activities that apply machine learning to data, with the goal of reducing non-productive drilling time and lowering drilling costs. As explained in Chapter 3 and Appendix C, lowering drilling costs and reducing overall development costs are essential to geothermal deployment.

SUB-ACTION 1.3.2: Increase technology and tool transfer from the oil and gas industry.

Many existing tools and technologies from the oil and gas industry could be leveraged for deployment in the geothermal industry, resulting in significant improvements in exploration and drilling success rates—and, in turn, reducing development costs. In some cases, barriers to this implementation are technical; for example, many potentially useful downhole tools cannot be deployed in geothermal wells due to temperature limitations of the electronics and hardware. As explained in Lowry et al. 2017, the main failure points within downhole components are the electronics, elastomers, and organic materials. Modifications using existing technologies can help accommodate the higher temperatures and often corrosive environments found in geothermal drilling.

Other areas of potential improvements to facilitate technology transfer include reducing polycrystalline drill-bit cutter wear and failure in hard-rock environments. Logging and measurement while drilling are also common technologies in the oil and gas industry that can reduce drilling costs by providing real-time information to optimize a drilling operation (Lowry et al. 2017). Research, development, and industry collaboration will be essential to addressing barriers that limit the transfer of these types of tools and technologies to the geothermal industry.

A related non-technical barrier is that drilling and wellfield service providers tend to focus on the existing, larger oil and gas markets, perceiving the geothermal market and growth potential to be too small to warrant the investments needed to port technologies across the two industries. Many providers may be unaware of the potential for geothermal market growth and the fact that—with relatively limited additional investment—



Experimental testing of a prototype polycrystalline diamond compact drill bit at Sandia National Laboratories' Hard-Rock Drilling Lab. Photo credit: Randy Montoya/Sandia National Laboratories

the geothermal industry could readily adapt oil and gas tools for geothermal applications. The *GeoVision* analysis helps illuminate geothermal industry potential. As explained in Chapter 4, if the TI scenario of the *GeoVision* analysis is achieved through stakeholder collaboration and the actions in this Roadmap, the geothermal industry would likely need to drill hundreds to thousands of additional wells per year. While not a direct comparison, in 2016, the domestic oil and gas industry drilled about 1,000 wells per month in the United States (EIA 2018). The potential impact on the U.S. drilling industry is apparent when considering the number of additional wells needing to be drilled and serviced. Such market growth is likely to draw attention from existing oil and gas service providers. This action is also related to Action Area 4, Improved Stakeholder Collaboration.

SUB-ACTION 1.3.3: Develop new drilling technologies, methods, and tools specific to geothermal environments.

Leveraging tools from the petroleum industry is one option to advance technology for geothermal environments (Sub-Action 1.3.2); however, transfer of existing technology from other industries alone is not adequate. The geothermal industry encounters high-

strength, hard-rock environments with distributed fracture permeability and extremely high temperatures, in some cases combined with high-gas, corrosive, and acidic environments. R&D on technologies that improve drilling processes and efficiencies in geothermal-specific environments can fill gaps that existing technology transfer cannot.

Technology advancements are needed in drilling hardware (e.g., drill bits, drill strings, mud motors), well construction materials (e.g., casing, cements), and drilling systems and methodologies (e.g., mud programs, advancing and cementing casing, innovative drilling approaches). As discussed in Lowry et al. 2017, key areas for improvement are likely to be early-stage research activities that reduce tangible costs, such as casing and cementing, as well as intangible costs, such as drilling time and non-drilling time.

Tangible drilling costs can be reduced through novel well designs and casing and cementing techniques that decrease the number of casing strings required. Non-tangible costs, especially non-drilling time, can result from issues such as difficulty cementing, wellbore instability, and equipment failures, but are caused most often by lost circulation and stuck pipes. Lost circulation occurs when drilling fluid flows into the geologic formation instead of returning to the surface; such losses are estimated to cost the oil and gas drilling industry \$1 billion per year in rig time, materials, and other financial resources and to add an estimated average of \$185,000 per well to geothermal rig costs (Lowry et al. 2017). Additional opportunities exist in technologies that can alter the rock ahead of the drill bit to make drilling easier and increase the rate of penetration while drilling. This will require research into geothermal applications of chemical-enhanced drilling, jet-assisted drilling, and laser-enhanced drilling. Developments and innovations will improve geothermal drilling success rates and drilling efficiency while reducing drilling times and development costs.

SUB-ACTION 1.3.4: Improve drilling decision making, operational culture, and efficiency.

Although many technology improvements are necessary to realize the deployment potential of geothermal energy projected in the *GeoVision* analysis, humans are ultimately required to make the critical decisions in geothermal developments and drilling operations. Human interactions and team dynamics are critical to leveraging data and information in the most impactful and beneficial way, and good

decision making drives efficient and low-cost drilling (Melosh 2017). Effective geothermal drilling decisions in uncertain conditions rely on accurate and reliable forecasting. Team-thinking and collaborative decision-making processes have been proven to reduce drilling costs (Melosh 2017). Even in the absence of innovative technology or hardware (tool) development, further research on and implementation of decision processes and organizational and management cultures that streamline approaches in geothermal drilling are expected to yield cost and efficiency improvements.

SUB-ACTION 1.3.5: Improve well life cycles.

Geothermal wells and wellbores are subjected to extreme temperature, pressure, and chemical conditions that can push well-construction materials to their limits—and, often, into modes of failure that result in significant repair costs for geothermal operators. Prolonging the life cycles of geothermal wells can reduce costs and significantly improve geothermal project economics because fewer make-up wells will be required over a project lifetime. Achieving this goal will require understanding root-cause failure modes, improving well engineering design and construction, and early-stage R&D to develop new and hardened construction materials that can withstand higher temperatures and corrosive environments. Tools and systems to monitor wellbore integrity once a well is completed and in service also need to be developed to establish a baseline condition against which an asset's performance and health can be measured over time. This will allow geothermal operators to make proactive management decisions that reduce development and operational costs.



Drilling at Don A. Campbell Geothermal Project in Mineral County, Nevada. Photo credit: Piyush Bakane

KEY ACTION 1.4 – Improve geothermal energy resource recovery

Technology advances could enhance rock-formation permeability and enable improved energy recovery across the geothermal spectrum.

DELIVERABLE(S): Methods that allow developers to better access geothermal heat and efficiently bring that heat to the surface for use in energy production and heating and cooling.

IMPACT(S): Increased well productivity and reduced risk of non-productive or sub-commercial wells. Increased development of hydrothermal resources through stimulation of non-productive wells. More efficient and cost-effective use of all geothermal resources, including low-temperature resources.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 1.4.1: Develop existing and innovative stimulation methods for improved geothermal resource recovery.	Improved methods for existing stimulation technologies. Innovative technologies and approaches to well and reservoir stimulation.	Higher probability of successful stimulation. Substantially reduced costs in conventional hydrothermal and enhanced geothermal system deployment for electric and non-electric applications. Improved well productivity and flow rates.
SUB-ACTION 1.4.2: Improve zonal-isolation techniques.	Technologies, methodologies, and best practices that ensure reliable zonal isolation in geothermal environments.	Reduced costs and operational risks. Improved economics for enhanced geothermal system projects.
SUB-ACTION 1.4.3: Develop advanced real-time fracture modeling and mapping.	Advanced real-time, integrated fracture mapping that enables operators to monitor progress in reservoir stimulation.	Actively managed stimulation operations, resulting in improved success rates, lower costs, and lower risk of induced seismicity.
SUB-ACTION 1.4.4: Quantify the relationship among <i>in-situ</i> state of stress, induced seismicity, and permeability.	Quantified relationship among relevant subsurface parameters.	Optimized reservoir permeability. Minimized hazards from induced seismicity.
SUB-ACTION 1.4.5: Improve heat-exchange mechanisms and system design for geothermal heat pumps.	Advanced ground heat exchangers for residential and commercial uses.	Reduced cost and land use for geothermal heat pumps and direct-use systems. Improved efficiency of geothermal heat pump systems.

Rationale for Actions

SUB-ACTION 1.4.1: Develop existing and innovative stimulation technologies for improved geothermal resource recovery.

The potential widespread geothermal deployment outlined in the *GeoVision* analysis—supported in great part by EGS resources—will require developing cost-competitive, effective, and reliable stimulation methods. The success of EGS is contingent on the ability of the industry to predictably and reliably stimulate economic reservoir volumes from downhole points of access. Achieving this will require overcoming

large gaps in existing knowledge of the mechanism by which stimulation occurs; that is, whether is it from creating new fractures, shearing existing fractures, or a combination of both. Without this understanding, stimulation is a hit-or-miss activity with little or no guarantee of success (Lowry et al. 2017).

Stimulation is used to enhance the natural permeability of a reservoir so that fluids can flow and heat extraction can be achieved in a more cost-effective manner. The goal is to establish an efficient and cost-effective fracture network in hot rock with an initial

low permeability. Developing existing and innovative stimulation technologies will have a direct and critical impact on improving well flow rates and, thus, rates of geothermal energy recovery. Achieving this will mean overcoming a fundamental economic limitation for EGS development, where capital costs are not yet commercially competitive. As illustrated in Table 3-3 and Appendix C, a doubling of well flow rates and a 10-fold increase in well productivity are necessary to reduce capital costs of EGS development to the point that wells can support commercial rates of energy extraction and achieve the 60-GW_e EGS deployment levels indicated in the *GeoVision* TI scenario.

Stimulation is also used in maintaining and managing conventional hydrothermal systems to rejuvenate underperforming systems or extend them to increase overall capacity. This activity could include the conversion of non-productive wells to productive assets that can support economic power production on conventional hydrothermal systems, thus reducing project capital costs.

Stimulation falls into two broad categories, with significantly different methods of implementation and results: 1) high-pressure, low-volume stimulation techniques commonly applied in the tight oil industry, and 2) low-pressure, high-volume stimulation that can be a byproduct of injection commonly performed in most existing geothermal fields. These two stimulation approaches may ultimately be applied in concert to create economic EGS reservoirs—starting in the in-field EGS environment and progressing outward toward deep-EGS resources. Geothermal fracture networks are distinct from those created for hydrocarbon recovery, and opportunity exists to continue to adapt oil and gas stimulation methods to conventional geothermal uses. However, it is likely that early-stage R&D will be required to develop an entirely new class of stimulation technologies and approaches that can make EGS economically viable.

On the R&D pathway to this ultimate goal of economic EGS, the geothermal industry generally recognizes that low-pressure, high-volume stimulation has produced notable successes where it has been applied to in-field EGS environments. It is not clear, however, why this has been successful; i.e., what are the underlying subsurface processes that drive stimulation, and how

do they interact to create sustainable permeability? EGS reservoir conditions, production flow rates, temperatures, pressures, and fluid chemistries are unique, and the coupled thermal-hydraulic-mechanical-chemical processes that control these geothermal conditions are not well understood. Research into these processes, as well as influence and constraints placed on them by the local and regional stress states, will be critical to improving success rates of existing stimulation methods and laying the knowledge base necessary for innovative stimulation methods for deep, high-temperature, high-pressure EGS environments.



Raft River geothermal power plant in Idaho.
Photo credit: Roxie Crouch

SUB-ACTION 1.4.2: Improve zonal-isolation techniques.

The ability to successfully isolate zones within a borehole for stimulation purposes is critical for EGS success. Zonal-isolation technologies adapted from the oil and gas industry—such as those used in unconventional shale plays—as well as new zonal-isolation technologies developed specifically for geothermal applications will play an integral part in the ability to control fracture location and initiation. Designing zonal-isolation strategies requires fully understanding the local and regional states of geological stress through improved collection of geomechanical data and understanding the impacts of pumping rates and fluid chemistries on stimulation. This sub-action is a critical companion to Sub-Action 1.4.1 and will support the objective to improve geothermal stimulation. The ultimate impact will be reducing capital costs to the point that EGS developments can be commercially competitive.

SUB-ACTION 1.4.3: Develop advanced real-time fracture modeling and mapping.

The ability to reliably predict permeability changes during stimulation in both conventional hydrothermal and EGS reservoirs will require improved models. These models should incorporate real-time changes in well pressure, temperature, and chemistry to understand dynamic reservoir processes and their impacts on reservoir sustainability and opportunities for optimization.

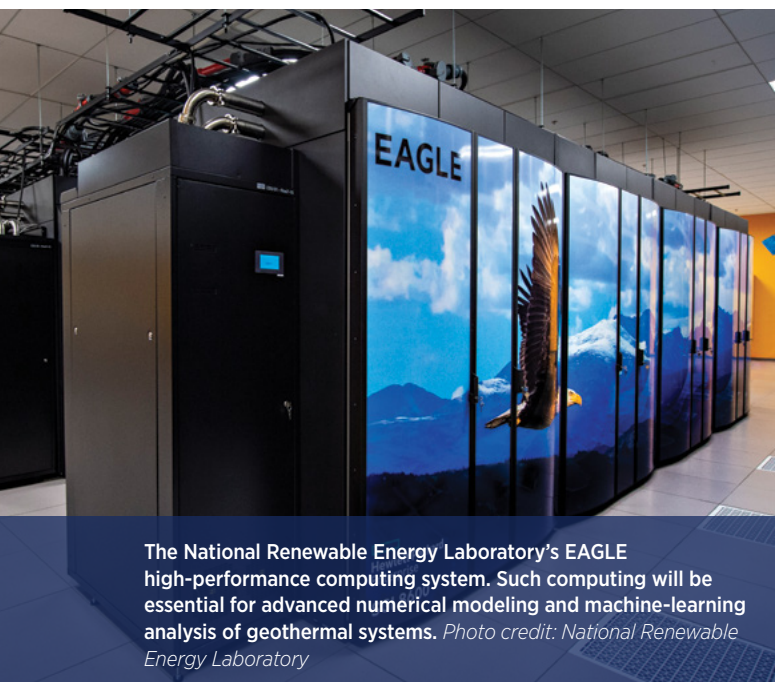
Robust field-scale fracture models that can help predict system performance are essential for creating and managing EGS reservoirs. Developing such models requires a fundamental understanding of the fracturing process and advanced real-time fracture mapping that enables operators to monitor the progress and success of a well-stimulation operation. Improved fracture models that are fully integrated with thermal-hydraulic-mechanical-chemical controls and real-time, georeferenced micro-earthquake data will advance this area of research.

SUB-ACTION 1.4.4: Quantify the relationship between *in-situ* state of stress, induced seismicity, and permeability.

Understanding the complex relationships among stress state, seismicity, and permeability is critical to creating functional and economic EGS reservoirs and managing their long-term sustainability. Predicting long-term permeability behavior is complex and requires an understanding of the interrelated effects of pressure, fluid chemistry, temperature, stress, and flow-rate variability. To date, industry has only been able to identify empirical links among these phenomena, and experimental results are often independent from one another. Coupled thermal-hydraulic-mechanical-chemical models that provide response feedback information will constrain the most critical parameters impacting permeability. Identifying and coupling these mechanisms in robust models could allow operators to adjust field strategies quickly, optimizing manipulation of permeability while minimizing induced-seismicity hazards.

SUB-ACTION 1.4.5: Improve heat-exchange mechanisms and system design for geothermal heat pumps.

Additional R&D in heat-exchange mechanisms and improved software tools can significantly reduce costs and improve performance of ground heat exchangers used in GHP systems. Innovation and technology advancements are needed to develop new ground heat exchangers. Ground heat exchangers using deep boreholes can be less expensive in some subsurface systems and are needed for applications where available land is limited. Alternative heat-exchanger designs—such as developing helical heat-exchange loops and using foundation piles as heat exchangers as elaborated in Liu et al. 2019—show promise in lowering costs and increasing performance. In addition, large GHP systems for commercial applications could be made more energy efficient through optimized system design using advanced software and other design tools. Improvements and technology breakthroughs could reduce heat-exchange loop costs by as much as 30%. Enhancing heat-pump efficiencies by as much as 50% by 2030 is also achievable through technology breakthroughs that include developing and implementing variable-speed compressors and dual-stage heat pumps dual-stage heat pumps (Liu et al. 2019).



The National Renewable Energy Laboratory's EAGLE high-performance computing system. Such computing will be essential for advanced numerical modeling and machine-learning analysis of geothermal systems. Photo credit: National Renewable Energy Laboratory

KEY ACTION 1.5 – Improve geothermal resource and asset monitoring, modeling, and management

Accurate forecasting of fluid flow through geothermal reservoirs can allow better management of production from associated resources.

DELIVERABLE(S): Improved methods and tools that allow developers to monitor and model geothermal resources.

IMPACT(S): Improved sustainability and more efficient and cost-effective management of geothermal resources.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 1.5.1: Improve monitoring, modeling, and forecasting of reservoir performance.	Improved, integrated, and coupled full-field (reservoir-steamfield-power plant) models and forecasting.	Improved resource sustainability and project economics. Reduced costs and improved geothermal economics.
SUB-ACTION 1.5.2: Develop advanced reservoir tracers and tracer-deployment techniques.	Innovative tracers and tracer-deployment methods and monitoring tools that allow for continuous monitoring for tracer returns.	Improved monitoring, management, and characterization of geothermal resources. Reduced costs and improved geothermal economics.

Rationale for Actions

SUB-ACTION 1.5.1: Improve monitoring, modeling, and forecasting of reservoir performance.

Resource monitoring serves two primary purposes in reservoir management: 1) establishing the baseline status of the system and 2) creating a record of reservoir responses and performance over time that can be assessed to continually optimize the system. Cost restrictions often limit the amount of monitoring data collected at geothermal operations. Adequate monitoring data are needed for developing and integrating models of geothermal reservoirs, steamfields, power stations, and other infrastructure. If integrated appropriately, these data could be used to forecast system performance and plan major capital expenditures. The quality, resolution, and predictive ability of the models on which these data are built is critical. Improved monitoring, modeling, and forecasting tools—including applications of machine learning technologies—could support better and more timely decision making and resource management, which can reduce the number of make-up wells that need to be drilled on an operating field. The ultimate impact would be reduced geothermal development costs and improved project economics.

SUB-ACTION 1.5.2: Develop advanced reservoir tracers and tracer-deployment techniques.

Effective geothermal field management requires identifying and understanding the dynamic response and evolution of reservoir heat flow, permeability, pressure, and fluid chemistry to changes in field operations. Reservoir tracer tests facilitate understanding of these critical relationships at depth and over relatively large distances. Tracer tests also provide an understanding of changes in reservoir hydrology in response to production and injection activities.

Existing tracers and tracer test data and interpretation techniques provide only limited spatial resolution of the reservoir characteristics (Hawkins et al. 2017). Innovative tracers, tracer test methodologies, and interpretation techniques can maximize the value of test data and improve reservoir management in conventional hydrothermal and EGS reservoirs. Improved knowledge of subsurface fluid flow and temperature distributions and their changes in response to operational activities (production and injection) will support improved field management and sustainable geothermal generation. The overall impact will be to reduce operational costs and improve the economics of geothermal energy.

Action Area 2: Regulatory Process Optimization

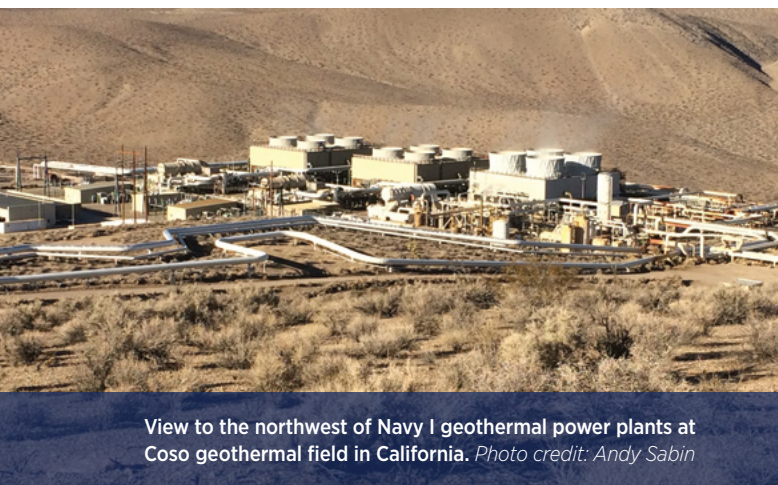
Regulatory processes are essential in helping to ensure that geothermal development is carried out responsibly and consistently. However, geothermal regulations have evolved over time in separate instances, resulting in processes that are often inefficient and complex. In addition, regulatory processes do not always account for advances in technology, changes in the energy market, or other factors.

Overcoming complexity and uncertainty in costs and development timelines resulting from regulatory processes can support increased geothermal deployment. The *GeoVision* analysis confirmed that shortening permitting and regulatory process times alone can result in increased exploration and a higher rate of geothermal project development over the status quo; increased deployment projected to occur through

improved regulatory timelines would occur even in the absence of technology improvements. Because 90% of conventional geothermal resources in the United States are located on federally managed lands (Young et al. 2014), collaboration among agencies with land-management responsibilities will be essential to optimizing regulatory processes. Action Area 2 includes activities for stakeholders to evaluate and navigate regulatory processes, not to propose requirements or modifications to regulations. These actions rely on collaborative processes, careful and objective analysis, and consideration for a range of stakeholder needs.

It was beyond the scope of the *GeoVision* analysis to identify or propose policy changes, and no attempt is being made to do so in this section. The activities in Action Area 2 focus on reviewing and researching the effects of regulation on the geothermal industry to help inform decisions and provide understanding for the industry.

KEY ACTION 2.1 – Improve land access		
Streamlined processes for leasing lands with prospective or known geothermal resources could expedite development of those resources.		
DELIVERABLE(S): Optimized and standardized leasing and land-access processes.		
IMPACT(S): Increased discovery of geothermal resources. Reduced construction timelines, risk, and costs for development.		
SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 2.1.1: Evaluate geothermal leasing processes for federal lands and examine potential opportunities to improve such processes.	Optimized and consistent leasing processes for geothermal development on federal lands.	Potential for increased discovery rate of geothermal resources. Potential to shorten project timelines and improve project economics.
SUB-ACTION 2.1.2: Improve ability to deploy geothermal energy for electricity and direct use on U.S. military bases.	Collaborative and comprehensive report on the potential for geothermal energy applications on military bases.	Improved national security through reliability and resiliency provided by geothermal electricity generation and heating and cooling on military bases.
SUB-ACTION 2.1.3: Examine opportunities for standardized permitting processes.	Standardized and coordinated processes across federal and state organizations.	Shortened review time and consistent requirements. Shorter project timelines. Improved project economics.



View to the northwest of Navy I geothermal power plants at Coso geothermal field in California. Photo credit: Andy Sabin

Rationale for Actions

SUB-ACTION 2.1.1: Evaluate geothermal leasing processes for federal lands and examine potential opportunities to improve such processes.

The length of time from the start of exploration to the day on which a geothermal operation produces power and begins generating revenue is generally 8–10 years (Young et al. 2019). The overall development timeline may be even longer than that as a result of requirements associated with processing a lease nomination, and some lease stipulations may prevent development entirely (Young et al. 2014, Young et al. 2019). Although a federal or state land-management agency can nominate lands for leasing (i.e., request that those lands be made available for development), nominations typically come from prospective developers—especially at the federal level.¹⁰¹ Before the responsible land-management agency (e.g., the Bureau of Land Management) can lease federal or state lands, the agency typically must complete a pre-leasing analysis and post the land for lease sale.¹⁰² This process results in a Lease Sale Queue that has historically taken as long as five years on federally managed land (Bureau of Land Management and U.S. Forest Service 2008). Examining opportunities to streamline lease processing and requirements can simplify the leasing process for both agencies and developers. Streamlining could allow stakeholders to address leasing issues in a consistent and collaborative manner, potentially mitigating impediments to project development and enhancing

opportunities for responsible geothermal development on public lands. Collaboration among agencies with land-management jurisdiction will be vital in examining lease process improvements that account for all stakeholder needs.

SUB-ACTION 2.1.2: Improve ability to deploy geothermal energy for electricity and direct use on U.S. military bases.

Military installations have a demand for power and are motivated to be energy independent to help ensure security of operations. Geothermal development could help military bases meet mission requirements and prevent grid encroachment through extended transmission and distribution power lines. The Department of Defense’s Geothermal Program Office has the authority to explore, develop, and sell geothermal resources on military installations, as defined in 10 USC 2916 and 2917 (Levine and Young 2017); however, potentially developable resources on military installations are not yet developed (Meade et al. 2011, Alm et al. 2012). A collaborative effort to evaluate the potential for geothermal installations on military bases and to clarify appropriate land-management authorities could open military sites for geothermal development—in turn, potentially helping to provide energy security for military operations.

SUB-ACTION 2.1.3: Examine opportunities for standardized permitting processes.

As discussed in Section 2.4, developing a geothermal project requires a variety of permits, and—although federal permits are the same nationwide—state permits can vary widely. Administrative procedures to obtain permits involve several federal, regional, and local authorities, and the complex and sometimes time-consuming procedures can impact the investment potential of a geothermal project because of extensive delays and varied requirements (Young et al. 2019).

Coordinated federal and state permit offices are in place to manage the required permit applications and environmental reviews of permits for projects involving oil and gas, mining, solar energy, wind power, and other large infrastructure projects (Young et al.

¹⁰¹ In a geothermal lease nomination, an entity (e.g., developer) requests to lease a parcel to develop geothermal resources, at which point a federal—or, in some cases, state—agency reviews the nomination. In some cases, a federal or state agency may not receive a lease nomination, but may determine on its own that it wants to lease the parcel.

¹⁰² Where another federal agency manages the surface estate above the geothermal resources managed by the Bureau of Land Management, such as the Forest Service, the surface manager only conducts the pre-leasing analysis (including compliance with the National Environmental Policy Act of 1969) and provides the Bureau of Land Management with a “concurrence” to lease the underlying mineral rights. The Forest Service does not nominate lands or post them for lease sale.

KEY ACTION 2.2 – Improve the ability to develop geothermal energy in accessible lands

A new model for permitting lands for geothermal energy use could enable market forces to drive future development through improved regulatory processes.

DELIVERABLE(S): Tools and strategies that simplify market access while mitigating environmental impacts.

IMPACT(S): More efficient, cost-effective, and environmentally sound access to geothermal resources.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 2.2.1: Study the potential for streamlining environmental review and permitting of geothermal development activities.	A report of the potential for and benefits of streamlining reviews of geothermal activities on federally managed lands.	Understanding of how streamlined reviews could reduce exploration costs and risks for developers.
SUB-ACTION 2.2.2: Develop innovative strategies to minimize and mitigate environmental impacts during geothermal siting and development.	Mitigation measures that facilitate geothermal development while reducing environmental impacts.	Ensured protection of environmental, biological, cultural, tribal, and archeological resources while allowing geothermal development.
SUB-ACTION 2.2.3: Collaborate among local, state, and federal stakeholders to examine strategies to improve market access.	Strategies to address financial and market barriers to geothermal power development.	Better access to power purchase agreements for new geothermal developments.

2019). The *GeoVision* analysis confirms that permitting improvements and efficiencies could be realized through a number of mechanisms and could lead to expanded geothermal deployment. Collaborative efforts to examine these mechanisms and their impacts could identify opportunities to improve geothermal permitting.

Rationale for Actions

SUB-ACTION 2.2.1: Study the potential for streamlining environmental review and permitting of geothermal development activities.

Many permitting reviews for federal land use are based on important considerations for preserving the environmental quality, ecological health, and overall aesthetics of public lands. Accommodating those requirements is essential to ensuring long-term protection for and quality of such locations.

Geothermal projects that are on federally managed land and/or receiving federal funding may be subject to an environmental review process under the National Environmental Policy Act (NEPA) as many as six times—from the land-use planning phase through use of the geothermal resource (as determined through analysis of the geothermal NEPA review process in Young et al. 2014).

As described in Section 2.4, the type of NEPA review process required (i.e., categorical exclusion, Environmental Assessment, Environmental Impact Statement) depends on the complexity of the activity being permitted; decisions about how the process is conducted can impact overall geothermal development timelines. Identifying opportunities for streamlining permitting processes for geothermal development could decrease the cost and time associated with

geothermal exploration and resource confirmation. These findings can be used to advance discussions and motivate further investigation of tools such as programmatic analyses, categorical exclusions, and/or streamlining of other environmental reviews as a means to help accelerate geothermal project development while accommodating and respecting crucial protections.

SUB-ACTION 2.2.2: Develop innovative strategies to minimize and mitigate environmental impacts during geothermal siting and development.

As noted in Sub-Action 2.2.1, responsible energy development requires accounting for considerations that preserve the environmental quality, ecological health, and overall aesthetics of U.S. lands. To further enable geothermal development, the industry can develop new—and improve on existing—strategies to minimize impacts during the early stages of geothermal development. In addition, mitigation techniques used by other industries (e.g., using temporary roads) can allow development with minimal surface impact. Applying similar measures to geothermal energy projects could potentially allow geothermal development to proceed more efficiently and in more areas.

SUB-ACTION 2.2.3: Collaborate among local, state, and federal stakeholders to examine strategies to improve market access.

Difficulty in financing geothermal projects—accessing capital and acquiring power purchase agreements—is the greatest non-technical barrier to geothermal projects being developed in the United States (Wall and Young 2016). Removing hurdles to obtaining power purchase agreements and capital could significantly increase geothermal development. In addition, state-level renewable portfolio standards are often not applied evenly among technologies and—as currently implemented—tend to hinder geothermal energy. Collaboration among stakeholders can help support strategies to address financial and market barriers such as disparities in incentive programs. Strategies could include: 1) support for increased deployment of renewable technologies that exhibit flexible-generation characteristics and can operate in either a traditional “baseload” configuration or as load-following generation, 2) programs that support increased geothermal deployment, and 3) changes in market-pricing structures to address asymmetries across energy technologies.

KEY ACTION 2.3 – Evaluate geothermal heat-pump regulatory processes

Standardized local permitting and building codes, based on statewide policies, can improve acceptance of GHPs in heating, ventilation, and air-conditioning markets.

DELIVERABLE(S): Analyses that can identify optimized policies and benefits for GHP applications.

IMPACT(S): Increased consumer interest and improved economics for GHP applications.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 2.3.1: Analyze the impacts of policies related to geothermal heat pumps.	Study of the potential for and impacts of state-level policies to improve geothermal heat-pump access and deployment.	Increased understanding of geothermal heat-pump policy impacts.
SUB-ACTION 2.3.2: Collaborate to evaluate tax credits and other programs for geothermal heat pumps that are similar to those for other technologies.	Study of tax credits and other programs for installation of geothermal heat pumps.	Increased deployment of geothermal heat pumps through reduced upfront installation costs.

Rationale for Actions

SUB-ACTION 2.3.1: Analyze the impacts of policies related to geothermal heat pumps.

The use of GHPs for heating and cooling can provide societal and environmental benefits, but the initial installation costs of such systems are usually more costly than conventional systems. In addition, state-level policies that mandate the adoption of renewable energy have not included GHPs as an eligible resource because heat pumps do not produce electricity that can be metered. Some states, however, have started to recognize GHP as a renewable technology and are allowing utilities to consider GHP systems to meet goals. Deploying GHP systems increases energy efficiency and can result in demand-side management improvements; however, the full impact of policies on the GHP market is not yet well understood. Analyzing these impacts is essential for informing policymakers and the GHP industry on where resources can be best leveraged. Policy analysis can also help identify opportunities to reduce cost, improve installation quality, increase public awareness, and encourage investments in GHP technology.

SUB-ACTION 2.3.2: Collaborate to evaluate tax credits and other programs for geothermal heat pumps that are similar to those for other technologies.

Tax credits, rebates, and other incentive programs have been proven to encourage consumer acceptance of GHP technology by partially defraying installation costs for investment and production (Hughes and Pratsch 2002, Liu et al. 2019). Further examining the efficacy of federal, state, and local benefits and incentives on GHP deployment can help policymakers, industry, and consumers evaluate opportunities for cost-effective GHP use. This understanding could help the nation employ appropriate incentives to realize benefits from increased use of GHPs.



High-voltage power lines transmit reliable and renewable geothermal electricity to American consumers.

Photo credit: National Renewable Energy Laboratory

Action Area 3: Maximizing the Full Value of Geothermal Energy

Geothermal energy is a renewable and diverse domestic energy solution for the United States—delivering reliable and flexible electricity generation as well as serving heating and cooling needs. Leveraging “always-on” and broadly available geothermal resources can provide a range of benefits, including grid stability, reliability, and resiliency; efficient residential and commercial heating and cooling; environmental improvements; and geothermal industry growth. However, the benefits that geothermal brings are not always valued fully in the marketplace.

Action Area 3 presents actions that can help the United States realize these benefits by encouraging geothermal development and improving geothermal project economics for both the electric and non-electric sectors. These actions are intended to address improvements in economic and revenue structures that extend beyond levelized cost of electricity or levelized cost of heat. Activities in this area focus on assessing economic barriers; creating new geothermal business models; investigating geothermal-hybrid applications; and assessing value-added markets for geothermal, such as desalination and mineral recovery.

KEY ACTION 3.1 – Improve valuation of and compensation for geothermal energy

Accurately capturing the value of geothermal resources across electric and non-electric uses can help support a viable, cost-effective alternative to other power sources.

DELIVERABLE(S): Analyses and understanding of and opportunities for geothermal energy.

IMPACT(S): Increased opportunities to realize additional value from geothermal technologies.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 3.1.1: Quantify the value that geothermal resources can provide to stakeholders.	Identification and quantification of the value that geothermal energy provides.	Defined areas in which the value of geothermal energy can be leveraged and improved.
SUB-ACTION 3.1.2: Improve data and education to financial institutions for geothermal power, direct-use applications, and geothermal heat pumps.	Comprehensive fact sheets and other educational tools for lenders.	Better lender understanding of geothermal projects, leading to increased availability of geothermal financing programs.
SUB-ACTION 3.1.3: Determine the impacts of financing structures on geothermal drilling.	Identification of existing and new financing structures that could be applied to the geothermal industry. Techno-economic analysis on the impact of financing structures on drilling.	Improved geothermal project financing and reduced financing costs. Shortened construction timelines. Increased exploration and capture of undiscovered resources.

Rationale for Actions

SUB-ACTION 3.1.1: Quantify the value that geothermal resources can provide to stakeholders.

Success in geothermal project development depends partly on awareness of the complete set of benefits that geothermal energy can provide. As discussed in previous chapters, benefits of increased geothermal deployment could include geothermal industry growth, improved air quality, and grid stability and resilience provided through load-following (dispatchable) capabilities and ancillary services. These impacts can be complex to quantify and are often not included in analyses of electricity markets that only focus on levelized costs of electricity or valued in traditional power purchase agreements for geothermal energy. Stakeholders must be able to quantify the value of the resource in order for geothermal energy to be valued accurately in the market. Some recent power purchase agreements have included valuation of services such as regulation and ramping (Edmunds et al. 2014), but further analysis is warranted to better understand all values provided by electricity-generation sources. Analyses that determine values for capacity, ancillary

services, storage, and transmission can help provide a more complete picture of the value of geothermal energy and allow the United States to realize the full benefits of geothermal deployment.

SUB-ACTION 3.1.2: Improve data and education to financial institutions for geothermal power, direct-use applications, and geothermal heat pumps.

Geothermal technologies are not widely known or understood in the United States. This lack of understanding and knowledge can lead commercial banks and lenders to mischaracterize the risk of geothermal projects. This concern spans the geothermal energy spectrum, affecting both electric and non-electric applications.

For conventional hydrothermal and EGS power and direct-use applications, the amount of data needed to prove an economic resource can be overwhelming, even to investors with geothermal knowledge. The need for large volumes of data can lead to miscommunication in project risk, which can ultimately drive higher financing rates. Standard data reporting and information can

improve communication and education, thus helping to improve investor confidence and reduce the cost of financing.

For GHPs, investors need a standardized and reliable way of quantifying benefits. Educational programs and case studies of installed GHPs could provide investors with detailed and potentially quantified comparisons between GHPs and conventional heating and cooling (Liu et al. 2019). Blockchain technology—which would provide a decentralized, autonomous ledger of transactions that cannot be corrupted or hacked—may also factor into future deployment of GHP and direct-use systems.

SUB-ACTION 3.1.3: Determine the impacts of financing structures on geothermal drilling.

Geothermal drilling is an inherently risky proposition—an issue that is highly integrated with development costs and resource uncertainties. Increased resource risk also presents challenges in obtaining project financing. Identifying mechanisms that could help shift risk from developers, reduce upfront exploration costs, and improve access to financing could impact geothermal drilling and help reduce development costs through improved financing. This action focuses on identifying existing and new financing structures that could be applied to geothermal and includes a techno-economic analysis of the effect of these structures on geothermal drilling activities.

KEY ACTION 3.2 – Investigate geothermal hybrid opportunities		
Integrating geothermal energy with other energy sources can enhance the production of reliable, flexible power.		
DELIVERABLE(S): Analyses and understanding of opportunities for geothermal hybrid (multifuel and multiapplication) technologies.		
IMPACT(S): Increased opportunities to realize additional value from geothermal technologies.		
SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 3.2.1: Develop commercially viable applications of geothermal paired with solar, coal, natural gas, and energy storage.	Identification of opportunities to develop and deploy technologies that allow for geothermal to be paired with other energy sources.	Improved efficiency of geothermal generation. Increased reliability of variable energy sources. Efficient energy-storage applications.
SUB-ACTION 3.2.2: Improve hybrid power-plant configurations to increase efficiency at various operating conditions.	Analysis of geothermal-hybrid configurations that can improve power-plant efficiency.	Improved power-plant configurations that facilitate or aid in flexible geothermal power-plant operations.
SUB-ACTION 3.2.3: Analyze the thermal management of geothermal reservoirs for various hybrid power-plant configurations.	Analysis that investigates the potential for subsurface thermal energy storage and its impact on lifetime reservoir thermal management.	Potential to maintain or increase output, even in the event of a decrease in geothermal resource productivity. Extended life of geothermal resources.
SUB-ACTION 3.2.4: Develop modeling tools to evaluate multisource power generation for geothermal-hybrid systems.	A flexible model that can be used to evaluate and optimize multisource power-generation output.	Optimized power generation from multisource hybrid systems without a lag in power output. Reduced fuel costs at fossil fuel power plants and lower levelized cost of electricity than stand-alone power plants.

Rationale for Actions

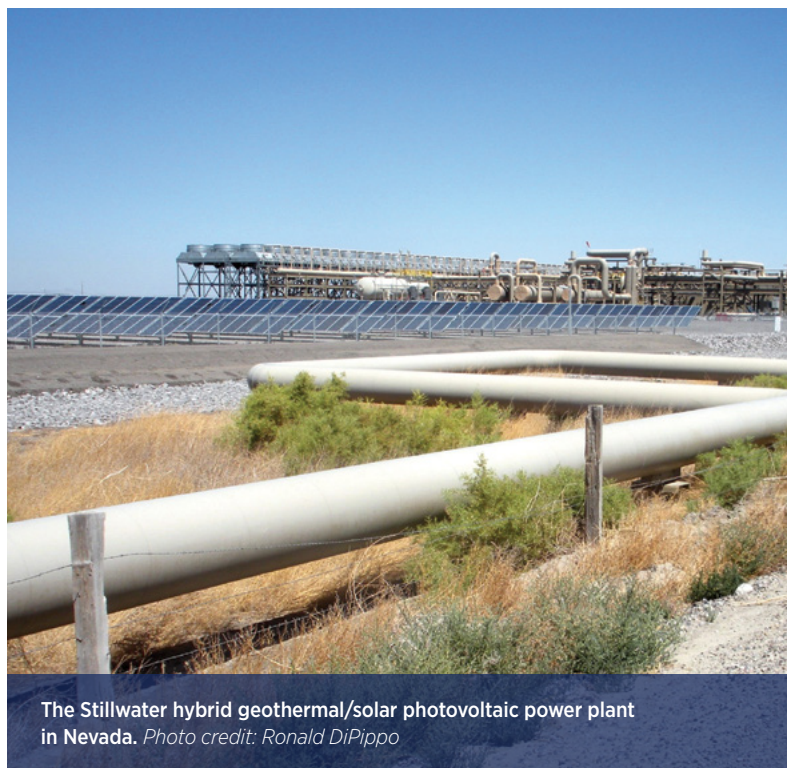
SUB-ACTION 3.2.1: Develop commercially viable applications of geothermal paired with solar, coal, natural gas, and energy storage.

Due to its versatility, geothermal energy can be matched and integrated with many other energy sources to produce reliable, flexible power production. Deploying geothermal energy in tandem with another technology can have benefits over both technologies being deployed alone. Some technologies and configurations of hybrid energy systems were explored in the *GeoVision* analysis, but there are others that were beyond the scope of the analysis. The explored hybrid systems can be improved on by reducing costs, scaling up, and increasing efficiencies to support commercial deployment. In turn, hybrid systems can lower the risks and costs of geothermal deployment by using existing infrastructure or improving an under-producing or declining geothermal resource.

The use of hybrid technologies can assist in making flexible operation of geothermal plants commercially viable and could help stabilize the electric grid. Geothermal power plants can operate in a load-following configuration; however, the curtailment of geothermal generation during periods of over-generation or off-peak demand can lead to revenue loss and impacts on the plant infrastructure, reservoir permeability, and long-term thermal management of the reservoir. Hybridization may be able to mitigate these impacts; for example, incorporating solar with thermal energy storage may allow for time-shifting of both the solar and geothermal generation. Onsite thermal uses (e.g., hydrogen production, mineral recovery, thermal desalination) can provide thermal demand response while geothermal electricity generation is being curtailed. Additional research is needed across these areas.

SUB-ACTION 3.2.2: Improve hybrid power-plant configurations to increase efficiency at various operating conditions.

Many configurations of geothermal-hybrid power plants include operating the plant at variable or off-design conditions. For instance, in certain hybrid configurations, the operating conditions may cycle daily, or it might benefit grid operations to operate hybrid plants in a flexible mode, where they can run in a load-following setting. Analytical tools that help achieve the highest efficiencies and identify the ancillary grid services that maximize the value of geothermal hybrid plants can improve performance of hybrid power plants that operate in such conditions. In addition to analytical tools, entirely new power-plant designs could be developed to maximize efficiency at partial-load conditions.



The Stillwater hybrid geothermal/solar photovoltaic power plant in Nevada. Photo credit: Ronald DiPippo

SUB-ACTION 3.2.3: Analyze the thermal management of geothermal reservoirs for various hybrid power-plant configurations.

Pairing geothermal energy with a variable thermal resource, such as concentrated solar power, opens the opportunity for subsurface thermal energy storage. This use could be examined in applications such as borehole thermal energy storage or aquifer thermal energy storage. Hybrid approaches could also directly impact the life-cycle thermal management of the geothermal reservoir itself, and each configuration of a hybrid plant will have differing impacts on the thermal management of the system. Analyzing the various attributes and opportunities of hybrid systems can help identify new options for managing geothermal reservoirs. In addition to site-specific considerations, pertinent variables for analysis include greenfield versus brownfield designs, whether or not the system includes surface thermal energy storage, considerations of how to incorporate disparate heat sources into the thermodynamic cycle, and the long-term effects of reservoir thermal management.

SUB-ACTION 3.2.4: Develop modeling tools to evaluate multisource power generation for geothermal-hybrid systems.

Modeling advancements were discussed with respect to geothermal energy systems in various actions under Action Area 1: Research Related to Resource Assessments, Improved Site Characterization, and Key Technology Advancements. Advanced modeling is also required to optimize the impact of geothermal-hybrid systems. Exploring the technical potential and economic viability of geothermal hybrid power plants with new modeling tools will help to identify commercial opportunities to demonstrate and deploy hybrid systems. Enhanced modeling can include improving the assessment of pairing geothermal with coal or natural-gas combined-cycle plants as described in the *GeoVision* analysis or going beyond to assess hybrid plants that integrate geothermal with multiple fuel sources.

KEY ACTION 3.3 – Quantify additional geothermal value streams

Additional geothermal value streams, such as tapping the desalination potential of geothermal energy and recovering dissolved solids from geothermal fluids, can help address the country’s water and critical materials issues and create added revenue opportunities for geothermal operations.

DELIVERABLE(S): Analyses of additional geothermal value streams, including new potential value streams.

IMPACT(S): Increased opportunities to realize additional revenue and value from geothermal technologies.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 3.3.1: Conduct techno-economic feasibility analysis of developing and commercializing thermal-desalination technologies.	Cost-effective thermal-desalination methods and processes.	Establishment of economic viability of using geothermal heat to desalinate non-freshwater sources.
SUB-ACTION 3.3.2: Analyze potential and develop advanced technologies for cost-effective and commercial-scale mineral recovery.	Economically feasible methods and processes to recover minerals from geothermal fluids at the commercial scale.	Ability to economically extract valuable and strategic materials from geothermal fluids. Cost-effective extraction of strategically important resources from geothermal brines.
SUB-ACTION 3.3.3: Develop and evaluate other innovative value streams for geothermal technologies.	Discovery and evaluation of additional value streams to pair with geothermal systems.	Increased value and potential revenue for existing and new geothermal projects.

Rationale for Actions

SUB-ACTION 3.3.1: Conduct techno-economic feasibility analysis of developing and commercializing thermal-desalination technologies.

The process of desalination removes salts from brines, brackish water, or saltwater to create freshwater. The use of geothermal power in desalination applications is promising because geothermal brine can provide both an energy source and a potential feedstock for such an application. In addition, geothermal resources frequently occur where water is scarce, such as in the arid western United States. Investigating the market opportunities for thermal desalination will help developers and stakeholders understand how to best develop and integrate desalination into geothermal development.

This action requires a geographic confluence of a non-freshwater water source, available geothermal heat, and a market for the treated water. The opportunity is that the heat requirements for thermal-desalination processes are often available from geothermal sources that are not being used. This means that, although there may be substantial capital costs to deploy a geothermal desalination system, the operating cost for the energy to drive the process would be lower than other desalination systems. Validating pilot-scale demonstrations can support scale-up of existing systems.

Initial niche uses for geothermal desalination, such as treating waters from oil and gas production, could help scale technologies and reduce system costs. Deployment opportunities could potentially be increased by pairing desalination with EGS resources. Such resources have the advantage of being deployable to supply the thermal-energy demand for desalination at locations where hydrothermal resources do not exist but brackish or saline aquifers are present for use as feedstock to the desalination process. This would offer needed flexibility toward meeting desalination co-location requirements. Ultimately, co-location issues—rather than cost targets—are likely to provide the greatest barriers to widespread deployment of geothermal-based desalination projects. The use of widespread EGS resources in combination with lower-cost desalination technologies is likely to help address these barriers.

In applications where the primary driver for installation of a desalination plant is the demand for purified water, geothermal desalination is expected to be more cost competitive when using higher-temperature geothermal resources. The economics of geothermal desalination are likely to continue to improve with better plant performance and lower costs, especially as freshwater scarcity impacts water-stressed regions of the country.



Sapphire Pool in Biscuit Basin at Yellowstone National Park, Wyoming. Photo credit: Jim Stimac

SUB-ACTION 3.3.2: Analyze potential and develop advanced technologies for cost-effective and commercial-scale mineral recovery.

Geothermal brines often contain dissolved solids that include valuable and strategic minerals. Findings in Neupane and Wendt 2017 indicate that, for geothermal brines with high mineral potential, mineral-extraction plants co-located with power plants could help make geothermal power more cost effective. However, extracting these minerals can be cost prohibitive. Establishing mineral-extraction facilities at any candidate sites will first require characterizing the most valuable minerals and evaluating extraction technology, capital/operating costs, and market forces. Essential steps to the viability of mineral recovery from geothermal brines include developing methods to recover dissolved minerals and ways to process high volumes of fluids with relatively low concentrations of target minerals and a range of fluid qualities. Realizing this additional value stream will require research to continue to evaluate methodologies and test innovative approaches at pilot scale.

Exploring extraction technologies at locations with the largest concentrations of minerals with commercial potential may provide the greatest initial impact. Experience by an early adopter could help scale up many components of the technology to become commercially viable for other locations. In the longer term, market segments of interest include: 1) extractions of critical minerals that address national security concerns and strategic demands, 2) recovery of high-value minerals that can provide additional revenue streams to improve economics of geothermal power production, and 3) minerals of high abundance (e.g., silica) whose removal can improve geothermal plant performance with some potential added revenue.

Additional steps in combining mineral extraction with geothermal power generation may include identifying opportunities for power production to be sited alongside existing mining operations and to use the

associated fluids, establishing an industry consortium to scale up and commercially deploy geothermal mineral-extraction technologies, and publishing parameters and goals on the economic viability of geothermal brines for strategic and critical materials.

SUB-ACTION 3.3.3: Develop and evaluate other innovative value streams for geothermal technologies.

The *GeoVision* analysis included a broad but not exhaustive look at numerous potential value streams to improve the economics of geothermal development (Wendt et al. 2018). As innovations continue across the geothermal industry and related sectors, additional opportunities may become available. The technical and economic potential of each new opportunity will need to be evaluated with quantitative modeling tools. This will enable stakeholders to accurately assess the prospects and incorporate the most promising options into existing operations and new developments.

KEY ACTION 3.4 – Assess the economic barriers and solutions pertaining to direct-use applications and geothermal heat pumps		
Better understanding of markets suitable for geothermal heat pumps and direct-use systems could promote greater penetration of geothermal applications into those markets.		
DELIVERABLE(S): Studies and models that facilitate understanding of the economic conditions for and value of geothermal heat pumps and direct-use systems.		
IMPACT(S): Increased industry and consumer interest in geothermal heat pumps.		
SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 3.4.1: Perform in-depth studies of economic barriers for geothermal heat pumps and direct-use applications.	Studies that identify underlying economic and market conditions and barriers as well as the most viable future deployments of geothermal heat pumps and direct-use systems.	Established record of the state of geothermal heat pump and direct-use economic conditions.
SUB-ACTION 3.4.2: Improve techno-economic modeling for geothermal heat pumps and direct-use systems.	Publicly accessible techno-economic models for project assessment.	Optimized use of geothermal heat pump and direct-use systems to meet cost-saving and energy-performance goals.
SUB-ACTION 3.4.3: Engage realtor and appraiser industries to develop a better understanding of the value of geothermal heat pumps in home appraisals and sales.	Understanding of and models for the value of geothermal heat pumps in the appraisal of real-estate property market value.	Full accounting of the effects of geothermal heat pumps on market value in new and resale homes.

Rationale for Actions

SUB-ACTION 3.4.1: Perform in-depth studies of economic barriers for geothermal heat pumps and direct-use applications.

Market studies for GHPs have been ongoing since the 1990s. As market conditions change over time, so does the ability of GHPs to capture market share. Tracking GHP installation and shipment data will help provide a complete dataset for domestic use of such technologies and can facilitate extended studies and analysis. Periodic GHP market studies should be performed to capture trends and identify possible remedies for declining or stalled market share, as well as to identify areas that are most viable for future deployment. Studies can be used to update the GHP industry and related stakeholders on the installation base (capacity, characteristics, and geographical distribution of GHP projects), field performance, growth rate, barriers, and R&D needs. Direct-use market studies for applications such as district heating should also be performed on a periodic basis, starting with a baseline analysis.

Any future market studies should include actual field performance of GHPs and direct-use systems, which is important to enable third-party financing and other policies related to financial incentives. Data on performance could also provide important insights to evaluate the impact of state policies on GHPs and direct-use systems.

SUB-ACTION 3.4.2: Improve techno-economic modeling for geothermal heat pumps and direct-use systems.

Improved techno-economic modeling for both GHPs and direct-use applications will allow stakeholders to evaluate various options (technical and financial) in a timely, efficient manner. Models can simulate GHP and direct-use energy utilization in individual, clustered, and large buildings, and can be structured to support

urban-energy planning. Models could also be developed to assess technical and financial options for energy retrofits and new construction. A web-based tool could allow home owners, developers, and financiers to easily and quickly identify the best and most financially sound solutions to meet cost-saving and energy-performance goals. Modeling tools can be made broadly available on websites and in consumer-friendly modeling platforms.

SUB-ACTION 3.4.3: Engage realtor and appraiser industries to develop a better understanding of the value of geothermal heat pumps in home appraisals and sales.

Despite the acknowledged high efficiencies and long-term energy cost savings offered by GHPs, including ENERGY STAR® certification,¹⁰³ there is no generally accepted or standardized means of determining the value of GHPs in real-estate markets. A coordinated effort among geothermal stakeholders and the realtor and appraiser industries could help establish a mechanism to determine GHP value in real estate. This could provide a way for real-estate listings to reflect the value of GHPs accurately and help consumers better understand and potentially adopt GHPs.



Drilling and installation of a vertical closed-loop ground heat exchanger for a geothermal heat pump system. Photo credit: Ed Lohrenz/International Ground Source Heat Pump Association

¹⁰³ See the ENERGY STAR® website at https://www.energystar.gov/products/heating_cooling/heat_pumps_geothermal.

KEY ACTION 3.5 – Identify opportunities to improve standards, business models, and economics for direct-use applications and geothermal heat pumps

Integrating geothermal heat pumps and direct-use systems into commercial/industrial designs for large installations can lead to greater use of these geothermal technologies at all consumer levels.

DELIVERABLE(S): Analyses of consumer adoption rates for geothermal heat pumps and direct-use systems; standards and best practices related to system design.

IMPACT(S): Increased consumer adoption rates of geothermal heat pumps and direct-use systems.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 3.5.1: Standardize geothermal heat-pump system designs and installations.	Improved standards and a handbook of best practices for geothermal heat-pump system design and installations.	More accessible geothermal heat-pump financing. Wider industry compliance with state and local permitting requirements.
SUB-ACTION 3.5.2: Determine market-adoption rates for geothermal district-heating and cooling systems.	Market adoption and impact analysis for domestic geothermal district heating.	Potential for increased deployment of geothermal direct-use district heating and cooling.
SUB-ACTION 3.5.3: Identify opportunities to develop integrated business models for geothermal heat pumps and direct-use systems.	Business models that overcome high initial cost barriers.	Wider adoption of GHP and direct-use technologies.

Rationale for Actions

SUB-ACTION 3.5.1: Standardize geothermal heat-pump system designs and installations.

Case studies about GHPs have determined that more benefits can be achieved if the design and controls for GHP systems are standardized, including optimal system integration to maximize heat recovery and smarter control to avoid excessive pumping power (Liu et al. 2019). The GHP industry can benefit from established standards for design and installation of GHPs, along with a handbook of best practices, reviewed and possibly endorsed by professional organizations. Improved standardization of GHP systems and tools to communicate practices could help increase acceptance of the technology by builders, investors, and other related stakeholders.

SUB-ACTION 3.5.2: Determine market-adoption rates for geothermal district-heating and cooling systems.

Although geothermal district cooling is not a widely adopted technology—and, thus, not assessed in the *GeoVision* analysis—future technologies could increase opportunities for district cooling as well as district heating (which is assessed in the analysis). 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 at a market level is not

well understood. Nevertheless, deployment projections on the basis of economic potential are significant for the United States and demonstrate that this could be an area of industry growth. 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 U.S. market potential. Quantifying the market potential and related benefits of geothermal direct-use applications can raise awareness of the potential and encourage use of renewable, geothermal direct-use heating and cooling solutions in U.S. communities.

SUB-ACTION 3.5.3: Identify opportunities to develop integrated business models for geothermal heat pumps and direct-use systems.

Several barriers prevent rapid adoption of GHPs in the United States, including high upfront costs, poor public awareness, and lack of government support (Hughes 2008, New York State Energy Research and Development Authority 2017). Geothermal district heating and cooling systems also have high upfront costs and suffer from a lack of public awareness. Alternative business concepts, such as third-party ownership and associated business models, could help reduce barriers related to high initial cost for GHPs and direct-use applications. New business structures could also monetize energy savings and environmental benefits over the life span of the systems.

Other business- and market-related developments could reduce the cost of GHPs, including mass production of GHP equipment, large-scale GHP applications (e.g., GHP systems for campuses or large commercial buildings and building complexes) that take advantage of economies of scale, and vertically integrated business models (design, build, operate) to improve the efficacy and quality of GHP installations. Thorough analysis of business models and validation with pilot programs could help establish strategies to overcome high initial-cost barriers and raise awareness among stakeholders.



McGinness geothermal power plant in Nevada.
Photo credit: Haim Shoshan

Action Area 4: Improved Stakeholder Collaboration

Helping consumers, businesses, investors, and the prospective workforce to better understand the benefits and impacts of geothermal energy will require stakeholder collaboration and enhanced outreach. This work should include an ongoing effort to revise and update this Roadmap. Maintaining the Roadmap can help in overcoming economic, technical, and regulatory barriers to geothermal deployment as the industry evolves. In addition, expanded education and communication can raise public awareness of the benefits of geothermal energy and how challenges such as induced seismicity are addressed. This could improve public acceptance and help increase deployment and market penetration. In addition, growing the geothermal industry to the deployment levels identified in the *GeoVision* analysis will require developing and sustaining a qualified, well-trained workforce.

KEY ACTION 4.1 – Maintain the Roadmap as a vibrant, active process

Regularly updating the *GeoVision* Roadmap by tracking technology advancement and deployment progress can help engage stakeholders and identify priority geothermal R&D activities.

DELIVERABLE(S): Periodic reports on progress and updated Roadmap actions in response to technology advancements, deployment, and economic conditions.

IMPACT(S): Ongoing availability of up-to-date information and recommendations that inform and guide geothermal stakeholders in planning and decision making.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 4.1.1: Periodically update Roadmap progress and actions.	Updated Roadmap actions that account for geothermal technology advancements and changes in economic conditions.	Informed and up-to-date planning and decision making for the geothermal industry.

Rationale for Actions

SUB-ACTION 4.1.1: Periodically update Roadmap progress and actions.

This Roadmap is intended to be a living document that is regularly revised by a collaborative group of stakeholders. Using an evolving process of periodic reviews, informed by analysis, updates can be used as a means to discuss and reflect on progress toward the objectives and opportunities identified in the *GeoVision*

analysis. Periodic reviews will allow stakeholders to assess effects and revise activities, as necessary and appropriate, in response to changes in geothermal technologies, energy markets, industry and consumer needs, and other factors. Consistent review of the pathways identified in the *GeoVision* analysis will allow the Roadmap to reflect changing circumstances and maintain momentum toward increased geothermal deployment.

KEY ACTION 4.2 – Improve public education and outreach about geothermal energy

Effective public education and outreach strategies can inform the public about geothermal technologies and applications, leading to engagement and interest in the geothermal industry.

DELIVERABLE(S): Public awareness and outreach programs.

IMPACT(S): Increased public acceptance and awareness of geothermal technologies.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 4.2.1: Improve public education and outreach about geothermal power, geothermal heat pumps, and geothermal direct-use applications.	An actionable strategy for education and outreach across the geothermal spectrum.	Public engagement and interest in continuing the growth of the geothermal industry.

Rationale for Actions

SUB-ACTION 4.2.1: Improve public education and outreach about geothermal power, geothermal heat pumps, and geothermal direct-use applications.

Geothermal energy has a unique value proposition, providing electricity as well as non-electric applications for heating and cooling. A key factor for geothermal energy is perceived value in the eyes of the public, policymakers, and other stakeholders (Hanson and Richter 2017). For the non-electric sector, where geothermal resources are distributed and available nationwide, deployment tends to be hindered by a lack of education, outreach, and basic awareness of this cost-effective technology. In particular, GHPs lack appropriate business and financing models to incentivize consumers in selecting the technology for new construction and as retrofits on existing buildings.

The geothermal industry can benefit from a strategy for public outreach and education as well as a clear branding message that describes what geothermal energy is and what it can provide to the public. Collaboration across geothermal stakeholders can help develop and establish a consistent, credible, and compelling message. Stakeholders can leverage this message to create outreach tools, including effective use of social media. This effort can ultimately result in increased public awareness and interest in geothermal resources as an energy solution.

KEY ACTION 4.3 – Increase awareness of employment and training opportunities across all geothermal energy technologies

Evaluating and developing comprehensive employment and training programs can help attract and train the workforce required to meet the geothermal industry's long-term needs, ultimately providing long-term geothermal jobs.

DELIVERABLE(S): Training and educational resources intended to attract and inform a skilled geothermal workforce.

IMPACT(S): A workforce that is prepared to support growth and technological change in the geothermal industry.

SUB-ACTION(S)	DELIVERABLE(S)	IMPACT(S)
SUB-ACTION 4.3.1: Develop comprehensive training, workforce, apprenticeship, and educational programs in geothermal energy.	Geothermal education and certification programs at demonstration centers and other centers of higher learning.	Creation and maintenance of a trained and experienced workforce in geothermal development, deployment, and safety.
SUB-ACTION 4.3.2: Expand and foster international exchange and collaboration in geothermal energy.	Working international partnerships that benefit all stakeholders for sharing best practices, knowledge, and innovation.	Increased domestic and global engagement, communication, knowledge sharing, and collaboration.

Rationale for Actions

SUB-ACTION 4.3.1: Develop comprehensive training, workforce, apprenticeship, and educational programs in geothermal energy.

Workforce skills and practices are vital to growing the geothermal industry and helping support safety and efficiency. With increased geothermal deployment, greater numbers of trained professionals will be needed across the geothermal spectrum to satisfy demands for installation, construction, financing, regulation, operations, and maintenance across the geothermal spectrum. Additionally, trained salespeople and marketing experts will be essential to convey the technology's benefits to the public, policymakers, and other stakeholders. The geothermal industry can benefit from approaches similar to those of other renewable technology industries, such as wind power and solar energy, which have established training and licensing programs to develop robust and sustainable workforces experienced in installing and maintaining those systems.

Expanding effective geothermal training, education, and apprenticeship programs will help ensure availability of well-trained workers. Professional development of potential workforce members can be supported by geothermal-specific learning opportunities at multiple levels—from pre-college to trade—to ensure and maintain a high-quality workforce. Educational programs can be customized to meet the particular needs of a given region (e.g., regional differences in regulations, business opportunities, and public acceptance, as well as technical factors such as climate and geologic conditions). Educational and outreach programs can be modeled after similar successful initiatives, such as outreach efforts of the Geothermal Heat Pump Consortium, the DOE's Solar Decathlon, and others. Additional approaches, including apprenticeship programs, have been demonstrated as effective in other industries and could be implemented for geothermal technologies. Hands-on learning programs can foster interest in geothermal energy technologies and help both the workforce and the public understand associated benefits and opportunities.

SUB-ACTION 4.3.2: Expand and foster international exchange and collaboration in geothermal energy.

The U.S. geothermal industry does not exist in a vacuum—although the United States leads in many areas of geothermal deployment, other countries demonstrate leadership in various aspects of geothermal technologies. The action areas and sub-actions in the Roadmap can be supported through knowledge-sharing across the international and domestic industry.

The United States participates in a number of key international geothermal partnerships and associations. Engagement has historically been limited due to resource constraints and low participation. As a result, the domestic industry has not been able to realize the full benefit of associations, working groups, and partnerships. The *GeoVision* analysis highlights the opportunity and need for U.S. representatives to expand engagement in a way that positions the nation as a visionary leader in geothermal energy. Engaging more actively in international collaborations and investing in the international participation of key U.S. geothermal stakeholders can propel the industry forward across all geothermal energy sectors and technology applications.



Giraffes amidst Olkaria III geothermal piping at Hell's Gate National Park. Photo credit: Ormat Technologies, Inc.

References

GeoVision Analysis Supporting Task Force Reports

As noted in Chapter 1 and Appendix D, the *GeoVision* analysis relied on the collection, modeling, and assessment of robust datasets through U.S. Department of Energy national laboratory partners. Expert input was provided through seven technical task forces. The efforts of each task force resulted in at least one technical work product (report), identified as the *GeoVision* analysis supporting task force reports. Combined, these reports contain the foundational data and information for the *GeoVision* analysis and report; not all assumptions, results, and scenarios used in the analysis are contained within the main *GeoVision* analysis report. The full body of analytical work is available in the supporting task force reports identified in this reference list.

This list includes the supporting task force reports for quick reference. Appropriate citations for the supporting task force reports are also repeated in the chapter citations as necessary to confirm specific data references or refer the reader to additional details.

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Appendix A: Acronyms

National Laboratories	
INL	Idaho National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
SNL	Sandia National Laboratories
AEO	Annual Energy Outlook
ATB	Annual Technology Baseline
BAA	Balancing Authority Area
BAU	Business-as-Usual scenario (<i>GeoVision</i> analysis)
BLM	Bureau of Land Management (U.S. Department of the Interior)
BT	Breakthrough scenario (<i>GeoVision</i> analysis)
Btu	British thermal units
CAISO	California Independent System Operator
CAPEX	capital expenditure
CC	combined cycle
CCS	carbon capture and storage
CF	capacity factor
CO ₂	carbon dioxide
COP	coefficient of performance
CT	combustion turbine
CX	categorical exclusion
dGeo	Distributed Geothermal Market Demand
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
EA	Environmental Assessment
EER	energy efficiency ratio
EGS	enhanced geothermal system(s)
EIA	U.S. Energy Information Administration
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
EPAct	Energy Policy Act of 2005
FORGE	Frontier Observatory for Research in Geothermal Energy
FTE	full-time equivalent
GETEM	Geothermal Electricity Technology Evaluation Model

GHG	greenhouse gas(es)
GHP	geothermal heat pump
GHX	ground heat exchanger
GTO	Geothermal Technologies Office (U.S. Department of Energy)
GW _e	gigawatts-electric
GW _{th}	gigawatt(s)-thermal
GWH _{th}	gigawatt-hour(s)-thermal
HVAC	heating, ventilation, and air conditioning
IGCC	integrated gasification combined cycle
IGSM-CAM	Integrated Global System Model–Community Atmosphere Model
IQA	Information Quality Act
IRT	Improved Regulatory Timeline scenario (<i>GeoVision</i> analysis)
JEDI	Jobs and Economic Development Impact Model
km	kilometer(s)
kW	kilowatt(s)
LCOE	levelized cost of electricity
LCOH	levelized cost of heat
MMT	million metric tons
MW _e	megawatt(s)-electric
MWh	megawatt-hour(s)
MW _{th}	megawatt(s)-thermal
NEPA	National Environmental Policy Act
NF-EGS	near-field enhanced geothermal system(s)
NG-CC	natural gas combined cycle
NG-CT	natural gas combustion turbine
NO _x	nitrogen oxides
OGS	oil/gas steam turbine
O&M	operations and maintenance
PC	pulverized coal
PM _{2.5}	particulate matter (2.5 micrometers or smaller)
PPA	power purchase agreement
R&D	research and development
RE	renewable energy
ReEDS	Regional Energy Deployment System
SMU	Southern Methodist University
SO ₂	sulfur dioxide
TES	thermal energy storage
TI	Technology Improvement scenario (<i>GeoVision</i> analysis)
TRG	techno-resource group or technology resource group
USGS	U.S. Geological Survey
VAV	variable-air volume
WACC	weighted-average cost of capital

Appendix B: Glossary

Always on	Electricity generation operating at close to a 100% capacity factor (see “Capacity factor”)
Ancillary services	Capacity and energy services (e.g., operating reserve, frequency support, voltage support) that are used to ensure stable electricity delivery and optimized grid reliability. Also known as grid services
Bankable	A bank’s willingness to finance a project, based on demonstrable and sufficient collateral, future cash flow, and probability of success to be acceptable to institutional lenders for financing
Baseload	The minimum amount of power that a utility or distribution company must make available to its customers, or the amount of power required to meet minimum demands based on reasonable expectations of customer requirements
Binary-cycle power plant	A geothermal power plant in which the geothermal fluid heats and vaporizes a second fluid, called the working fluid or binary fluid, that passes through a closed-loop Rankine cycle for the production of energy
Black start	A process of restoring a power station to operation without relying on the external electric power transmission network
Blockchain technology	A digital ledger in which transactions are decentralized, recorded chronologically and publicly, and protected through cryptography
Blue-sky research	Concepts or ideas that are out of the mainstream of existing research and development, with the potential to provide large-scale (as opposed to incremental) advancement in a technology area
Brackish groundwater	Water containing 0.5–30 grams of salt per liter, expressed as 0.5–30 parts per thousand salt equivalents
Brownfield	A geothermal site that has had previous development of some type (e.g., former manufacturing site)
Capacity factor	A unitless ratio of actual electrical energy output over a given period of time to the maximum possible electrical energy output over the same period of time
Capacity payment	Payment (in a power purchase agreement) based on the capacity of an electricity generation facility, not the electricity it generates
Capital expenditures	Funds spent on the purchase, installation, and construction of physical power-plant components. For geothermal power plants, this includes the wellfield and power-generation equipment.
Caprock	Rock that acts as a confining or semiconfining layer or structure to a geothermal reservoir, usually rich in low-permeability clays that form as a result of hydrothermal rock alteration
Carbon-dioxide equivalents	A summation of the greenhouse gas effects of contributing gases (e.g., methane) measured on a carbon-dioxide equivalency basis
Categorical exclusion	A category of actions that do not individually or cumulatively have a significant effect on the human environment and that have been found to have no such effect on procedures adopted by a federal agency in implementation of these regulations (National Environmental Policy Act Sec. 1507.3) and for which, therefore, neither an Environmental Assessment nor an Environmental Impact Statement is required (40 Code of Federal Regulations 1508.4)
Coefficient of performance	The ratio of useful heating or cooling provided to the work required
Compressed-air energy storage	A method of storing previously generated energy in the form of compressed air for later use by conversion into potential energy

Confirmation well	Full-sized, completed production well with temperatures and flow rates sufficient for a commercial-size geothermal well (typically 3–5 MWe), drilled at the beginning of wellfield development to confirm the presence of a commercially viable geothermal resource
Conventional geothermal (or hydrothermal) resources	Geothermal resources that can be developed using existing technologies, including hydrothermal resources and geothermal heat-pump resources
Cooling ton	One cooling ton is equal to the amount of thermal energy required to melt one ton of ice in a 24-hour period (12,000 British thermal units/hour or ~3.5 kWth)
Cost of capital	Combined cost of debt and cost of equity for a project. Represents the minimum return a project must generate in order for it to be worthwhile financially.
Cumulative expenditures	Capital and operations and maintenance spending required over the analyzed timeframe to support deployment potential modeled in the <i>GeoVision</i> analysis
Curtailment	A typically involuntary reduction in the output of a generator from what it could otherwise produce given available resources
Desalination	A process of extracting salts and mineral components from saline water
Direct use	The practice of using thermal energy directly as opposed to converting it to another form of energy (usually electricity)
Discount rate	The interest rate used in discounted cash flow analysis to determine the present value of future cash flows
Discovery rate	The rate at which the undiscovered hydrothermal resource potential is assumed to become available for deployment in the Regional Energy Deployment System model (used in the <i>GeoVision</i> analysis), measured as a percentage of total undiscovered hydrothermal resources per year. Assumed to be constant and based on a uniform distribution of hydrothermal resources becoming available each year.
District heating	A system for distributing heat generated in a centralized location for residential and commercial heating requirements, such as space heating and water heating
Drilling success rate	The rate or ratio of full-sized wells in a geothermal field that have sufficient temperatures and production rates or injection rates to be used for commercial power generation, relative to those drilled that fail to meet those criteria
Dry-steam power plant	A power plant that uses geothermal steam (at or above the saturation point of water) to directly turn a turbine and generator without the need for separation of a liquid-water phase
Economic resource potential	A portion of technical resource potential that is cost effective to recover based on technology costs and anticipated revenues
Enhanced geothermal systems	Unconventional geothermal resources that contain heat similar to conventional hydrothermal resources but lack the necessary groundwater and/or rock characteristics (e.g., permeability) to enable economic energy extraction without innovative subsurface engineering and transformation
Enthalpy	A thermodynamic quantity equivalent to the total heat content of a system
Environmental Assessment	Public documents that a federal agency prepares as required by the National Environmental Policy Act to provide evidence sufficient to determine whether a proposed agency action would require preparation of an Environmental Impact Statement or a Finding of No Significant Impact
Environmental Impact Statement	A document under U.S. environmental law required by the National Environmental Policy Act for certain actions “significantly affecting the quality of the human environment”
Environmentally sensitive area	Designation for an area that needs special protection because of its landscape, wildlife, or historical value

Financing costs	Costs associated with borrowing money, including interest charges and other expenses
Fine particulate matter	A mixture of solid particles and liquid droplets found in the air (i.e., dust, vapor, and combustion particles). Fine particulate matter represents fine inhalable particles with diameters of 2.5 micrometers and smaller.
Flash-steam power plant	A geothermal power plant that requires processing of geothermal fluids to separate steam from water for the production of energy
Flexibility	The ability of the power system to respond to variations in supply and/or demand
Frequency regulation	Rapid, real-time balancing services for the electricity grid
Full-time equivalent	The ratio of total hours worked by a group of employees over a specified time period to compensable (working) hours in that same period
Fumarole	An opening in the Earth's crust—often in areas surrounding volcanoes—that emits steam and gases, such as carbon dioxide, sulfur dioxide, hydrogen chloride, and hydrogen sulfide
Generation	The act of producing electrical power from other energy forms (such as thermal, mechanical, chemical, or nuclear), or the amount of electrical energy produced; usually expressed in kilowatt-hours or megawatt-hours
Geophysical	A discipline of the Earth sciences that pertains to the physics of the Earth and uses the physical properties of the Earth to understand the Earth's systems and processes
Gigawatt(s)-electric (also gigawatt-hour[s]-electric, kilowatt[s]-electric, megawatt[s]-electric, megawatt-hour[s]-electric)	Power available in the form of electricity generated from the conversion of heat or other potential energy
Gigawatt(s)-thermal (also gigawatt-hour[s]-thermal, kilowatt[s]-thermal, megawatt[s]-thermal, terawatt-hour[s]-thermal)	Power available directly in the form of heat
Greenfield	A geothermal site where no previous development of any type has occurred
Heat pump	A mechanical-compression cycle system that can be reversed to either heat or cool a controlled space
High pressures	Pressures above lithostatic pressures, which are confining pressures or the pressures exerted on a layer of rock by the weight of the overlying material
Hybridization, hybrid application	A technology application that marries a geothermal technology to one or more additional energy-conversion technology or end-use applications
Hydrothermal	Referring to heat energy in the presence of water. Relating to or denoting the action of heated water in the Earth's crust.
Induced seismicity	Seismic activity (minor earthquakes and tremors) that are caused by anthropogenic activities that alter the stresses and strains on the Earth's crust
Injection	The practice of returning geofluids to a reservoir through a dedicated well
Injection well	A well through which fluids are injected into the earth (see "Injection")

Investment Tax Credit	A tax incentive that allows qualifying businesses to deduct a certain amount of money from their taxes based on capital investments in renewable energy projects
Levelized cost of electricity	The net present value of the unit cost of electricity over the lifetime of a generating asset
Levelized cost of heat	The net present value of the unit cost of thermal energy (heat) over the lifetime of a thermal energy source. Analogous to levelized cost of electricity but applies to direct-use geothermal resources.
Lithostatic pressures	Confining pressures or pressures exerted on a layer of rock by the weight of the overlying material
Load following	A power plant that adjusts its power output as demand for electricity fluctuates throughout the day. Load-following plants are typically in between baseload and peaking power plants in efficiency, speed of startup and shut down, construction cost, cost of electricity, and capacity factor.
Machine learning	An application of artificial intelligence that provides systems the ability to automatically learn and improve from experience without being explicitly programmed
Magmatic	Pertaining to magma or magmatism. Magma is a mixture of molten or semi-molten rock found beneath the surface of the Earth.
Magnetotelluric	An electromagnetic geophysical method for inferring the Earth's subsurface electrical conductivity from measurements of natural geomagnetic and geoelectric field variation at the Earth's surface
Market potential (also market resource potential)	An indication of how quickly resources could actually be adopted and deployed from the economic potential given market conditions such as regulatory environment, capital availability and investor interest, and consumer demand and energy competition over time
Microseismic	Any small seismic event that causes little or no damage or disturbance to surface infrastructure
Mineral recovery	The process of extracting commercially valuable minerals or other materials (solid compounds, gases, and others) from a geothermal fluid
Municipal wastewater	Domestic wastewater from households and municipal wastewater from communities (also called "sewage") containing physical, chemical, and biological pollutants
Nameplate capacity	The maximum output a generator can produce without exceeding design thermal limits, as determined by the manufacturer
Net electricity demand	Total electricity demand less demand met by generation from variable-generation renewable energy resources
Net load profile	Difference between forecasted load and expected electricity production from variable-generation electricity sources
Nonspinning reserves	Additional capacity that is not connected to the electrical grid system but can be made available to meet demand within a specified time
Overnight capital costs	The capital expenditure required to achieve commercial operation of a plant, excluding the construction period and the financing and interconnection costs
Payback period	Amount of time required for an investment to recover its initial expenditures (e.g., project development costs, installation costs) from its profits or savings
Peaking mode	Mode of power-plant operation in which plants turn on—or a reserved portion of plant capacity is used—to generate electricity when there is high or "peak" electricity demand. Peaking plants are typically fastest in speed of startup and shut down and most expensive in cost of electricity; as such, they are only used when electricity demand drives electricity prices.
Permeability	A measure of the ability of a porous material (rock or unconsolidated material) to allow fluids to pass through it

Pre-drilling exploration activities	Non-invasive activities that do not penetrate the surface through drilling, e.g., geological and structural mapping studies, remote-sensing data acquisition, geophysical surveys, and geochemical surveys
Production Tax Credit	U.S. federal, per-kilowatt-hour tax credit for electricity generated by qualified energy resources
Production well	Well that is used to produce geothermal fluids from the ground
Ramping (ramping mode)	Mode of power-plant operation in which plants substantially change power output over time frames of seconds to minutes in order to balance rapid changes in electricity supply or demand and provide grid stability. Plants operating in this mode “ramp up”—or produce more energy when electricity demand suddenly increases—and “ramp down”—or produce less energy when electricity demand suddenly decreases.
Renewable Portfolio Standard	Regulatory mandate to reach a defined level of production of energy from renewable resources, which may include geothermal, wind, solar, biomass and other alternatives to fossil and nuclear generation. Renewable portfolio standards are usually issued at the state and/or local level.
Replacement reserve	Power generation sources that are required to be available within a certain period of time (usually an hour or less) when operating reserves are used. Replacement reserves replace operating reserves in use to provide protection against additional unforeseen electricity demand increases or supply disruptions.
Reservoir	Underground volume from which geothermal energy is extracted
Resistivity	A quantification of the resistance of a material (the Earth’s crust) to the flow of electric current
Resource potential	The amount of power that could be generated from a particular resource. See “Technical resource potential,” “Economic resource potential,” and “Market resource potential.”
Seismic	Relating to earthquakes or other vibrations of the Earth and its crust
Set-aside (as part of a Renewable Portfolio Standard)	A technology-specific goal for renewable energy generation, such as 10% of generation from geothermal energy. Generally set at the state and/or local level.
Soft costs	Nonconstruction costs incurred before project commissioning, including public perception/educating the public, utilities, regulators, and policymakers; community education; risk; financing; permitting; legal fees; insurance; workforce availability and training (including installers and small drillers); political support (e.g., policies, political terms, and regional resources); power purchase agreements; and attracting large players (e.g., oil and gas companies)
Spinning reserve	Additional, rapidly available capacity from generating units that are operating at less than their capability
Stimulation (of a well)	An operation carried out on a well during or at the end of its productive life that increases production or injection by improving the flow characteristics of the reservoir drainage area, thus enhancing the flow between the reservoir and the wellbore
Stress state	State of geologic stress that characterize the force per unit area placed on rock
Summer net capacity	The maximum output, commonly expressed in megawatts, that generating equipment can supply to system load, as demonstrated by a multihour test at the time of summer peak demand (June 1–September 30). This output reflects a reduction in capacity as a result of electricity use for station service or auxiliaries.
Technical potential	The portion of the overall resource that can technically be accessed, considering limitations such as land access, physical access to the reservoir, and efficiency of equipment

Technical resource potential	Achievable energy generation given current technology, system performance, and environmental and land-use constraints
Thermal conductivity	The measure of a material's ability to conduct heat. In the context of geothermal heat pumps, the measure of the ability of a subsurface material (e.g., soil) to conduct heat to and from the ground loop of the geothermal heat-pump system.
Thermal-hydraulic-mechanical-chemical models	Dynamic numerical models of the heat-flow, geomechanical, and geochemical properties of an Earth system
Thermoelectric power generation	Electrical power generated indirectly through burning a fossil-fuel-based energy source
Tight oil and gas	Oil and gas found in relatively impermeable reservoir rock requiring stimulation using hydraulic fracturing to create sufficient permeability to allow hydrocarbons to flow at economic rates (see "Stimulation")
Tracers	Chemical compounds or isotopes that are artificially introduced to a hydrogeological system to fingerprint water types and their flow paths
Unconventional oil and gas	Oil and gas produced or extracted using techniques other than conventional methods. Typically refers to oil and gas produced or extracted using horizontal drilling and/or hydraulic fracturing to access oil and gas trapped in low- or ultra-low permeability rock formations.
Undiscovered resource	Hydrothermal resources that lack surface manifestations and are difficult to identify with existing exploration techniques and methods
Variable renewable generation	A renewable energy source that fluctuates because of natural circumstances not controlled by the operator
Volumetric	Relating to the measurement of volume
Volumetric well flow rate	The volume of fluid produced per unit time, typically reported as gallons per minute or liters/second
Water consumption	Water evaporated, transpired, and incorporated into products or crops or otherwise removed from the immediate water environment
Water withdrawal	Water removed or diverted from a water source for use
Weighted Average Cost of Capital	Calculation of the average cost of capital for all funding sources, such as debt and equity, for a project or company, in which each category of capital is proportionately weighted
Well productivity	The measure of a well's ability to flow; specifically, the flow rate into/out from a well for a given pressure differential between the reservoir pressure and wellbore pressure at the midpoint of a producing interval in a well
Zonal isolation	The process of operationally isolating specific intervals or zones along a wellbore to perform well intervention activities, such as stimulation

Appendix C: Detailed Modeling Assumptions and Results

This appendix contains additional details on technology cost assumptions, model inputs, and modeling results for the *GeoVision* analysis. Text and graphics were sourced from *GeoVision* analysis supporting task force reports (see References) and related national laboratory reports. This appendix focuses on the most influential and study-specific costs and inputs. For details about model methodology, inputs, and assumptions, and greater insights into results and conclusions, refer to the supporting task force and national laboratory reports.

C.1 Electric Sector

C.1.1 Expanded Discussion of Geothermal Resource Estimates

Geothermal resources capable of generating electricity are divided into four groups:

- Identified Hydrothermal Resources
- Undiscovered Hydrothermal Resources
- Near-Field Enhanced Geothermal Systems (NF-EGS)
- Deep Enhanced Geothermal Systems (Deep-EGS)

Descriptions of the development and results of these resource estimates are provided in the subsequent sections. Information and graphics in this section are sourced primarily from Augustine et al. 2019.

C.1.1.1 Identified Hydrothermal Resources

The U.S. Geological Survey (USGS) 2008 geothermal assessment (Williams et al. 2008) identified 241 moderate- and high-temperature (>90°C) sites on private or accessible public land in the United States. The sites are concentrated entirely within 13 states in the western United States, Alaska, and Hawaii. The methodology used to estimate the recoverable energy from each site identified in the assessment is described

in Williams et al. 2008. The USGS 2008 resource assessment predicts a mean total of 9,057 megawatts-electric (MW_e) of geothermal power-generation potential from identified hydrothermal systems on private or accessible public lands, with a 95% probability of at least 3,675 MW_e and a 5% probability of up to 16,457 MW_e of power-generation potential.

The total mean value of 9,057 MW_e for the recoverable electric-power-generation potential from the USGS 2008 assessment was adopted as the starting point for identified hydrothermal resources in the *GeoVision* analysis; site-specific data for the identified hydrothermal resources were obtained from the USGS (DeAngelo and Williams 2010). The *GeoVision* analysis applied a cutoff temperature of 110°C to this assessment database and considered only resources above this temperature threshold because cost estimates for resources at this temperature and below are prohibitively expensive. Adopting this temperature value results in the removal of 106 identified hydrothermal sites representing 460 MW_e of power-producing potential. Because of the low temperature of these removed resources, they are not likely to be commercially viable; as such, their exclusion should not impact the results of the Regional Energy Deployment System (ReEDS) modeling. The USGS 2008 assessment does not exclude currently installed generating capacity at identified hydrothermal sites. Data on installed geothermal capacity from the U.S. Energy Information Administration's (EIA's) EIA Form 860 (EIA 2016a) were used to remove existing capacity at USGS-identified hydrothermal sites. There were 2,542 MW_e of installed geothermal net summer capacity at the end of 2015, with 2,421 MW_e of this installed capacity at USGS-identified hydrothermal sites. According to these installed capacity data, some sites, such as The Geysers in California, have more existing installed capacity than potential capacity, so their potential was removed completely from the assessment. When installed capacity and sites with temperatures <110°C are removed from the USGS 2008

mean power-producing potential, the remaining mean potential capacity for identified hydrothermal sites in the United States is 6,370 MW_e. ReEDS (Section 3.1.2) only models the contiguous United States, so sites in Alaska and Hawaii were also removed. The result is that the remaining hydrothermal resource potential is 5,657 MW_e. Additional land restrictions identified in Young et al. 2019 further reduce the resource potential used as input for the ReEDS models to 5,078 MW_e for the *GeoVision* analysis Business-as-Usual (BAU) and Improved Regulatory Timeline (IRT) scenarios.¹⁰⁴ Assumptions about removal of some barriers (the *Land Access Improvement Scenario 2: Disruptive Improvement* in Young et al. 2019) increases the potential to 5,128 MW_e in the *GeoVision* analysis Technology Improvement (TI) scenario.

C.1.1.2 Undiscovered Hydrothermal Resources

In addition to identified hydrothermal resources, the USGS 2008 geothermal resource assessment estimated the power-production potential from undiscovered geothermal resources. USGS estimated the undiscovered resources for each state in the western United States using geographic information system-based statistical methods to analyze the correlation between spatial datasets and existing geothermal resources to derive the probability of the existence of geothermal resources in unexplored regions. The undiscovered geothermal resource power-generation potential from the study has a mean value of 30,033 MW_e, with a 95% probability of at least 7,917 MW_e and a 5% probability of up to 73,286 MW_e. The *GeoVision* analysis used the mean value of 30,033 MW_e; of this, 25,810 MW_e occurs in the contiguous United States. Land restrictions (Young et al. 2019) further reduce the value used as input for the ReEDS models to 18,830 MW_e for the BAU and IRT scenarios and 23,038 MW_e for the TI scenario.

The estimation of geothermal project costs in the Geothermal Electricity Technology Evaluation Model (GETEM) (Section 3.1.1) requires characterization of

the geothermal resource. However, the actual resource characteristics of the undiscovered hydrothermal resource, such as reservoir depth and temperature, are unknown. In the absence of this data, it was assumed that the undiscovered resources would be similar in nature to identified hydrothermal sites in the same region. To characterize the undiscovered hydrothermal resource, identified hydrothermal sites were first divided into the Balancing Authority Areas (BAAs) used in the ReEDS model. The identified sites were further divided into three subgroups by temperature: 1) sites with reservoir temperatures <140°C, likely not commercially viable; 2) sites with temperatures ≥140°C and <200°C, likely binary plants; and 3) sites with temperatures ≥200°C, likely flash plants.

For the *GeoVision* analysis, the mean potential capacity from identified hydrothermal resources in each BAA subgroup was totaled. The undiscovered hydrothermal resource in each state was first apportioned among BAAs—based on the percentage of identified hydrothermal resource in each BAA in a state—and then apportioned among the designated temperature ranges based on the percentage of identified hydrothermal resource in each subgroup. For several states, such as Colorado, the entire undiscovered resource was assumed to have a temperature <140°C because all the identified hydrothermal sites in those states have estimated reservoir temperatures <140°C.

Within each BAA, a single reservoir temperature, depth, and production well flow rate was assumed for the undiscovered resource in each temperature subgroup. The temperature, depth, and flow rate of the undiscovered hydrothermal resource in each subgroup was determined by calculating the mean capacity weighted average of each of those parameters from the identified hydrothermal sites in each subgroup. Because the reservoir characteristics were determined using the potential power capacity weighted average, the undiscovered resource is assumed to be more similar to the large identified hydrothermal sites in each state that have significant power-producing potential. This means, for example, that the high-temperature undiscovered

¹⁰⁴ The *GeoVision* analysis looked at three primary scenarios for evaluating the future potential of geothermal electricity generation in the United States: 1) Business-as-Usual (BAU): assumes that the geothermal industry continues on its current trajectory; 2) Improved Regulatory Timeline (IRT): assumes an improved regulatory environment leading to accelerated geothermal permitting processes and development timelines; and 3) Technology Improvement (TI): assumes a future where technology advances, cost reductions, and favorable financing options reduce the cost of geothermal technologies; includes IRT assumptions.

resource characteristics in California are heavily influenced by the characteristics of large sites such as The Geysers and the Salton Sea.

C.1.1.3 Near-Field Enhanced Geothermal System Resources

Near-field EGS resources consist of the areas around existing hydrothermal sites that lack sufficient permeability and/or *in-situ* fluids to be economically produced as a conventional hydrothermal resource. These resources require the application of EGS reservoir engineering techniques to become economic producers of electricity. Because these resources are proximal to existing hydrothermal sites, they tend to be relatively hot and shallow, and they are likely to be the first and least expensive EGS projects to be commercially developed. Estimates of near-field and deep-EGS potential around a selection of existing sites were developed as part of the USGS 2008 geothermal resource assessment. The USGS supplied a list of these sites, including estimates of the resource potential, temperature, depth, and location (Williams 2013). For areas around 21 producing hydrothermal fields considered in this study, the near-field EGS potential was 1,493 MW_e. Additional land restrictions (Young et al. 2019) further reduce the values used as input for the ReEDS models to 1,382 MW_e for the BAU and IRT scenarios and 1,443 MW_e for the TI scenario.

C.1.1.4 Deep Enhanced Geothermal System Resources

Deep-EGS resources consist of all the thermal energy stored in the Earth's crust at depths that can be accessed with existing drilling technology (but not necessarily developed with existing technology). The cost of electricity from an EGS site depends heavily on the depth and temperature of the reservoir to be developed. For the *GeoVision* analysis, the U.S. deep-EGS resource potential is defined as the thermal energy stored in rock at depths between 3 and 7 km below the Earth's surface, at temperatures exceeding 150°C, and within the contiguous United States. The deep-EGS resource potential estimate is based on temperature-at-depth maps developed by the Southern Methodist University (SMU) Geothermal

Laboratory (Blackwell et al. 2011). The deep-EGS electricity-generation resource-potential estimate was updated for the *GeoVision* analysis by Augustine 2016.

The *GeoVision* analysis used the following methodology to generate the resource-potential estimate: First, the subsurface is divided into intervals 1 km thick, similar to the SMU maps (Blackwell et al. 2011). Then, the amount of thermal energy in place in a given volume of rock is calculated assuming an overall average reservoir temperature decline of 10°C over the life of the reservoir. Next, the amount of this thermal energy that can be recovered is calculated, assuming a recovery factor of 20%. The recovered thermal energy is then converted to electric energy potential on a megawatts-electric per cubic kilometer (MW_e/km³) basis by a power plant at the surface, assuming a plant lifetime of 20 years and a power-plant conversion efficiency (DiPippo 2004) based on the temperature intervals from the SMU maps. Finally, the values of electric energy potential are used to estimate the electricity-generation potential at a location, based on the temperature values from the SMU maps.

The updated deep-EGS resource-potential estimate was calculated for rock at depths of 3–7 km with estimated temperatures exceeding 150°C. The results indicate a deep-EGS electricity-generation resource potential estimate of 5,157 gigawatts-electric (GW_e). A summary of the EGS electricity-generation potential for the contiguous United States, as a function of temperature and depth, is shown in Table C-1. The total deep-EGS resource is 5,156,956 MW_e. Identified land barriers (Young et al. 2019) reduce the deep-EGS resource estimate available in ReEDS to 3,375,275 MW_e for the BAU and IRT scenarios and to 4,248,879 MW_e for the IT scenario.

Deep-EGS Electricity-Generation Potential (MW _e)										
		Resource Temperature (°C)								
		150–175	175–200	200–225	225–250	250–275	275–300	300–325	325–350	>350
Depth (km)	3–4	74,217	2,592	100	—	—	—	—	—	—
	4–5	740,466	233,228	11,886	325	84	32	—	—	—
	5–6	517,601	724,689	373,680	57,281	4,654	195	128	—	—
	6–7	635,384	491,641	700,330	453,610	120,677	12,116	1,883	—	157

Table C-1. Updated Deep Enhanced Geothermal Systems Electricity-Generation Potential (MWe) for the Contiguous United States, Binned by Temperature and Depth Intervals (Augustine 2016)

C.1.2 Technology Cost and Performance Assumptions

As introduced in Section C.1.1, the *GeoVision* analysis looked at three primary scenarios for evaluating the future potential of geothermal electricity generation in the United States:

- **Business-as-Usual:** assumes that the geothermal industry continues on its current trajectory
- **Improved Regulatory Timeline:** assumes an improved regulatory environment leading to accelerated geothermal permitting processes and development timelines
- **Technology Improvement:** assumes a future where technology advances, cost reductions, and favorable financing options reduce the cost of geothermal technologies; includes IRT assumptions.

The scenario assumptions and values were used to develop cost and performance inputs for GETEM (Section 3.1.1). GETEM was run for each geothermal site or resource class, and the resulting project overnight capital costs¹⁰⁵ as well as operations and maintenance (O&M) costs outputs were used to develop the supply curves that serve as inputs to ReEDS. Because of the large number of geothermal sites, detailed site information was not considered when estimating costs in GETEM. Even though drilling costs can vary by

location, a single set of drilling cost curves was assumed for all sites.

Technology improvements can affect more than capital and O&M costs derived from GETEM. For example, technologies that decrease risk associated with geothermal projects can lower borrowing costs, and reductions in development timelines can lower the cost of financing. These factors are inputs in the ReEDS model and impact the net present value of a project. The impact of scenario assumptions on ReEDS inputs are discussed below and summarized in the discussion on the ReEDS model inputs (Section 3.2.1).

C.1.2.1 Business-as-Usual Scenario

The BAU scenario assumes cost and performance inputs for GETEM representative of existing technology and costs. Different inputs are applied depending on the technology type (hydrothermal or EGS). GETEM inputs are based on the default inputs in GETEM described in the *GETEM User Manual* (Mines 2016). In a project funded by the U.S. Department of Energy's Geothermal Technologies Office, a levelized cost of electricity (LCOE) analysis team developed these default inputs from 2011–2013. This team determined inputs through a series of interviews with industry subject-matter experts to validate the approaches used in GETEM and the reasonableness of estimated project-development costs.

¹⁰⁵ Overnight capital costs reflect the capital expenditure required to achieve commercial operation of a plant, excluding the construction period and the financing and interconnection costs.

The *GeoVision* analysis task forces also reviewed the default inputs for accuracy and reasonableness. The most significant change was the consideration of an updated set of drilling cost curves developed by the Reservoir Maintenance and Development Task Force (Lowry et al. 2017) in place of the default GETEM drilling cost curves (Figure C-1). A full list of default assumptions used in GETEM for the BAU scenario is provided in Augustine 2019.

The capital and O&M costs for all geothermal resources were estimated on a site-by-site basis using GETEM. First, site-specific resource definitions were input to GETEM, including resource temperature, depth to reservoir (i.e., drilling depth), technology type, plant type, and plant size. As in previous supply-curve reports (Petty and Porro 2007, Augustine 2011), a reservoir depth of 1.524 km (5,000 feet) was used when site-specific estimates were not available and was applied mostly to identified hydrothermal sites. Technology options considered include hydrothermal or flash steam, with the plant types being either 1) binary with temperatures less than 200°C, or 2) flash with temperatures equal to or greater than 200°C. EGS projects are always assumed to use binary plants with air-cooled condensers, which reinject all water that is produced from the reservoir, to minimize water requirements and potential scaling in the reservoir. Identified hydrothermal and near-field EGS plant sizes were based on resource potential and limited to a maximum size of 60 MW_e. If the resource targeted was larger than 60 MW_e, the analysis assumed that multiple plants would be developed at the site. For undiscovered hydrothermal and deep EGS, plant sizes of 25–40 MW_e were used.

C.1.2.2 Improved Regulatory Timeline Scenario

The IRT scenario explored the impact of an improved regulatory environment that leads to accelerated geothermal permitting processes and development timelines. The IRT scenario was based on analysis of non-technical barriers to geothermal deployment (Young et al. 2019), which considered a number of pathways and potential combinations of approaches to streamline and reduce project development timelines. The net impact of the IRT scenario was twofold. First, it

decreased the construction timeline. The hydrothermal construction timeline was shortened from eight years in the BAU scenario to four years in the IRT, and the EGS construction timeline was shortened from 10 years in the BAU scenario to five years in the IRT. Second, it increased the amount of resource exploration, resulting in an increase in the discovery rate for undiscovered geothermal resources from 1% per year to 3% per year.¹⁰⁶ This assumption was based on the following reasoning: decreasing the time it takes to get exploration permits can increase the amount of exploration that is performed each year, resulting in more resource discoveries per year. *GeoVision* Visionaries, including geothermal developers, reviewed this assumption and deemed it reasonable.

All remaining assumptions in the IRT scenario, including technology cost and performance values, were identical to the BAU scenario. Because the GETEM inputs were identical, the supply curves for the IRT scenario are the same as those for the BAU scenario. The financing assumptions used in ReEDS are also identical to the BAU scenario. The result is that the IRT scenario shows the impacts on geothermal deployment if soft costs, construction timelines, and barriers are reduced, even with current technology.

C.1.2.3 Technology Improvement Scenario

The TI scenario examined the impacts of aggressive technology advances and cost reductions developed by the *GeoVision* analysis task forces for use as GETEM inputs related to the potential for geothermal deployment. These improvements greatly benefit EGS, reducing costs to the point where EGS is commercially competitive. The improvements are also beneficial for hydrothermal technologies. The TI scenario incorporates the IRT scenario assumptions, which lead to both a threefold increase in the discovery rate of hydrothermal resources (from 1% per year to 3% per year) and a decrease in the project construction timelines. Technology improvements in exploration and drilling also lead to decreased project risk, which translates into reduced financing costs. The TI scenario assumed that geothermal projects are able to obtain financing at rates (weighted-average cost of capital) similar to other power-generation technologies.

¹⁰⁶ The 3% per year discovery rate is based on interviews with geothermal developers as part of the *GeoVision* analysis regarding the impact that decreased permitting times for activities associated with exploration would have on the amount of exploration developers could achieve in a given amount of time.

The TI scenario assumed that large utility-scale power plants continue to be the primary goal of project developers and that geothermal providers have advanced significant technology breakthroughs from a confluence of improvements. The improvements were developed by the *GeoVision* analysis task forces in their respective areas, based on analysis of existing and future technologies. Improvements were incorporated as GETEM inputs as part of the bottom-up analytical framework of the *GeoVision* analysis. Improvements

include, for example, the availability of big data to optimize exploration and drilling; advanced exploration drilling techniques such as micro-hole drilling; reductions in costs and improvements in drilling success rates overall; and the development of EGS techniques, such as multistage stimulation of horizontal wells that increase the productivity and longevity of EGS reservoirs. Changes to the GETEM inputs from the BAU scenario are summarized in Table C-2. The TI scenario assumed the BAU values for all other GETEM inputs.

GETEM Input		Business-as-Usual		Technology Improvement	
		Hydro	EGS	Hydro	EGS
RESOURCE EXPLORATION	Exploration – Pre-Drilling Costs (\$/project)	\$600K–\$1.2M	\$250K	Same as BAU	
	Exploration – Drilling Costs (\$/project)	\$3.3M–\$5.4M	\$1.5M–\$5M	2/3 of BAU	
	Full-Sized Confirmation Well Costs ¹⁰⁷	Base + 20%	Base + 50%	Ideal + 0% (no premium)	
	Full-Sized Confirmation Well Success Rate	50%	50%	75% (with stimulation)	
	Number of Full-Sized Confirmation Wells Required	3	9	3	
DRILLING	Drilling success rate	75%		90%	
	Drilling costs	Base		Ideal	
GEOFLUID GATHERING SYSTEM AND PUMPING		No changes			
RESERVOIR CREATION	Wells stimulated?	No	Yes	Yes	
	Well flow rate (flow rate per production well)	Binary: 110 kg/s Flash: 80 kg/s	40 kg/s	Binary: 110 kg/s Flash: 80 kg/s	
	Well productivity	4.6 kg/s/bar 5.8 gpm/psi	0.46 kg/s/bar 0.58 gpm/psi	4.6 kg/s/bar 5.8 gpm/psi	
O&M		No changes			
POWER PLANT		No changes			

Table C-2. Summary of Changes to Business-as-Usual Geothermal Electricity Technology Evaluation Model Inputs for Technology Improvement Scenario

*Table Notes: (1) Exploration pre-drilling activities typically involve geological, geophysical, and geochemical surveys. These surveys might include, but are not limited to, activities such as geological and structural mapping, remote-sensing data analysis, geophysical assessments of resistivity and temperature data, and geochemical surveys of groundwater and surface water and rock alteration. (2) The TI scenario assumes that the construction of large utility-scale power plants continues to be the predominant goal of project developers and that geothermal providers have advanced technology breakthroughs from a confluence of technology improvements. These improvements include the availability of big data to optimize exploration and drilling, advanced exploration drilling techniques such as micro-hole drilling, reductions in costs and improvements in the success rate of drilling overall, and the development of EGS techniques such as multistage stimulation of deviated wells that increase the productivity and longevity of EGS reservoirs. (3) The TI scenario assumes the BAU values for all other GETEM inputs. The *GeoVision* analysis used identical GETEM inputs for the geofluid gathering system and pumping, O&M, and power plant for both the BAU and TI scenarios. Values for these inputs can be found in Augustine et al. 2019. (3) kg/s = kilograms per second; kg/s/bar = kilograms per second per bar.*

¹⁰⁷ GETEM inputs were structured assuming that the costs of confirmation wells are more expensive than standard production wells drilled during the field-development phase. Costs of standard production wells are based on the drilling cost curves considered as the basis for the *GeoVision* analysis and as elaborated in Lowry et al. 2017. Costs of full-size confirmation wells consider the standard production well cost plus the indicated premium as a percentage of the standard well cost. Lowry et al. 2017 and Augustine et al. 2019 provide a complete description of geothermal well construction sizes, their cost-benefit relationships, and the manner in which costs are integrated within GETEM and the *GeoVision* analysis.

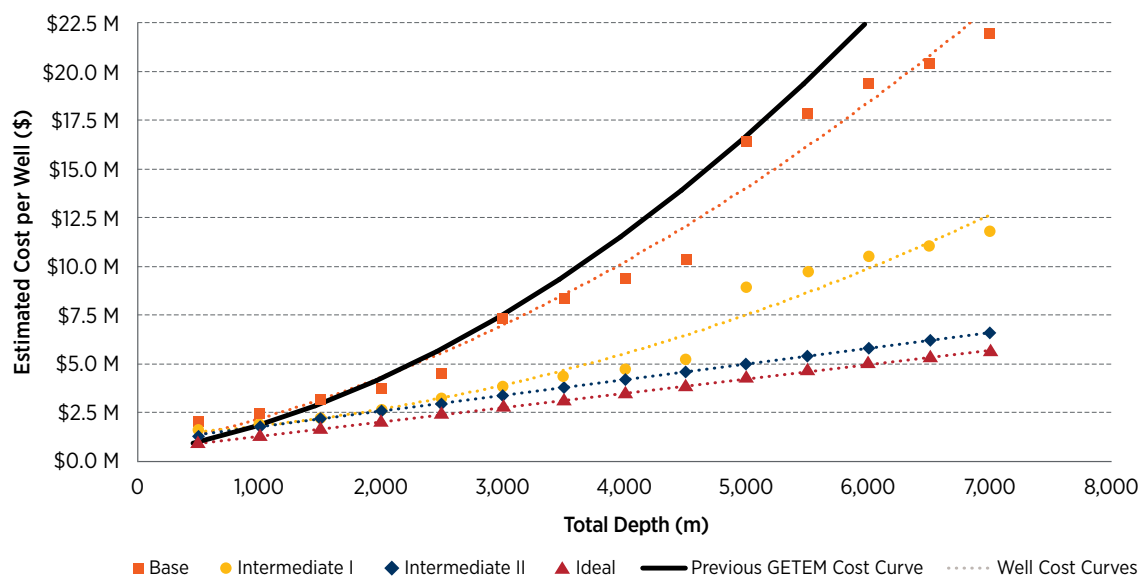


Figure C-1. Well-cost curves used in the *GeoVision* analysis (Lowry et al. 2017) relative to previous well-cost curve used in the Geothermal Electricity Technology Evaluation Model

Figure Note: Curves shown are for large-diameter vertical wells with an open hole. The TI scenario uses the Ideal cost curve.

Modeling assumptions with the largest impacts are drilling and well completion costs, and EGS reservoir creation and performance improvements. In the TI scenario, advances in drilling technology lead to significant reductions in drilling and well-completion costs for both hydrothermal and EGS. Based on research and analysis by the *GeoVision* analysis Reservoir Maintenance and Development Task Force, several well-cost curves were developed for the *GeoVision* analysis (Figure C-1). The “Ideal” well-cost curve was used for the TI scenario. Lowry et al. (2017) details the well-cost curves.

The TI scenario assumed that improvements in EGS technologies will allow for multistage stimulation of deviated wells in the creation of EGS reservoirs. The geothermal industry was assumed to be able to adapt directional drilling and multizonal isolation techniques from the oil and gas industry and to develop reservoir stimulation technologies to create EGS reservoirs with volumes and surface areas large enough to support

commercial production-well flow rates for decades. The result is that EGS reservoirs are assumed to have flow and productivity characteristics similar to hydrothermal reservoirs: production-well flow rates of 80 kg/s for flash plants and 110 kg/s for binary plants¹⁰⁸, and well injectivity/productivity index of 4.6 kg/s/bar.¹⁰⁹

Applying EGS technologies enables the replication of the high success rates seen in the unconventional-shale industry. Based on task force recommendations and reviews by *GeoVision* Visionaries, the *GeoVision* analysis assumed a 90% drilling success rate and a 90% stimulation success rate for EGS applications. Hydrothermal resources are also able to leverage EGS technologies for well stimulation to increase the effective well success rate, resulting in a 90% success rate with EGS techniques used on unproductive wells. With this 90% success rate, GETEM assumes that only unproductive wells (in the drilling phase) are stimulated.

¹⁰⁸ Binary plants generally have higher production-well flow rates than flash plants because the wells can be pumped to increase flow rates. Geothermal brine temperatures at flash plants are usually above the maximum operating temperature for downhole pumps or have two-phase (liquid and gas) flow in the well that would cause cavitation in the pump, and therefore they must be self-flowing.

¹⁰⁹ kg/s = kilograms per second; kg/s/bar = kilograms per second per bar

C.1.2.4 Geothermal Electricity-Sector Supply Curves

A supply curve is the combination of the technology resource potential and the cost to develop the resource. It shows how much of a resource is available and the cost of a given technology to develop that resource into a power plant to deliver electricity to the grid. When graphed as electricity-generation capacity versus cost, a supply curve is a visual representation of the amount of resource available for development as a function of cost. Supply curves that serve as inputs for the ReEDS model for geothermal electricity-generation resources were generated for each of the scenarios using the overnight capital costs derived from GETEM, based on the inputs for each scenario. The ReEDS model used the capital costs, along with model inputs such as financial parameters and construction timelines, to calculate the levelized cost of electricity for geothermal resources.

The resulting supply curves showing available new capacity as a function of overnight capital costs and levelized cost of electricity are shown in Figures C-2, C-3, and C-4. The supply curves for hydrothermal resources are shown in Figure C-2, and the supply curves for NF-EGS and deep EGS are shown in Figure C-3 and Figure C-4, respectively. Some axes have been truncated in Figures C-3 and C-4 to make the data readable (see Figure Notes). The BAU and IRT scenarios have identical capital cost supply curves, but their LCOE supply curves differ. This is because of the difference in construction timeline assumptions between the scenarios. The capacity for deep-EGS resources extends beyond 4,200,000 MW_e , and the overnight capital costs extend beyond \$100,000/ kW_e for the BAU scenario. Both of these values are irrelevant in practice, however, because it is unlikely that any resources at those costs would deploy in a BAU scenario. The overnight capital costs remain below \$10,000/ kW_e for the entire deep-EGS supply curve in the TI scenario. The BAU and IRT scenarios use the same supply curves as inputs for ReEDS.

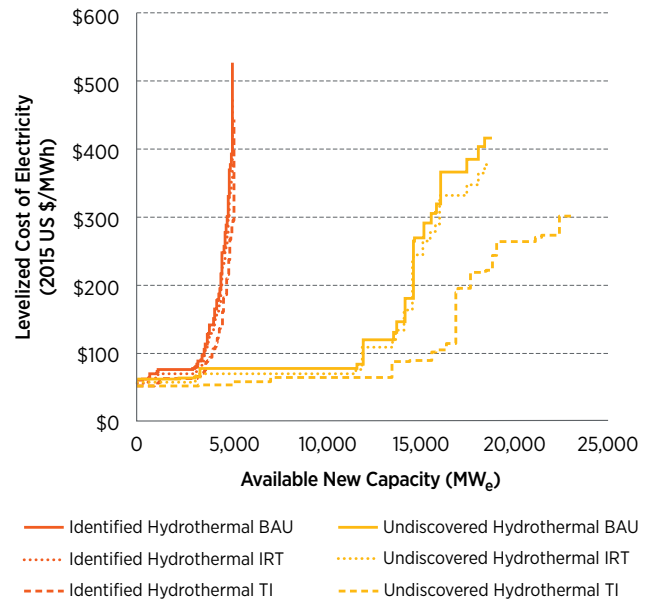
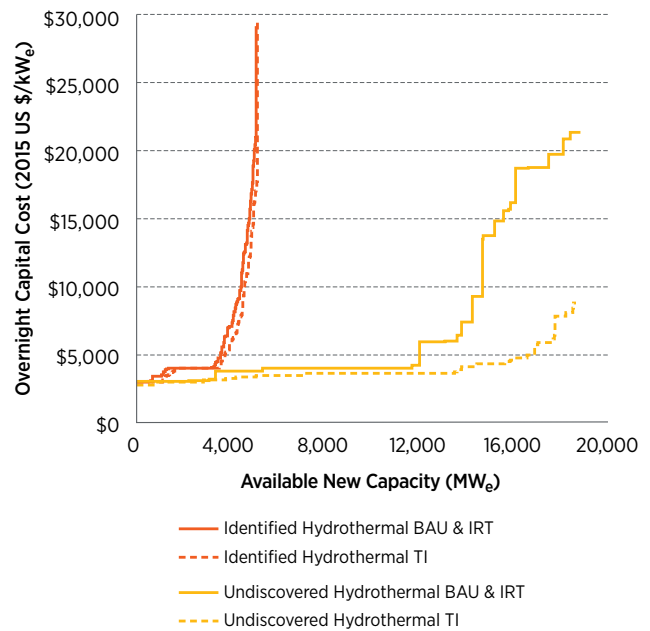


Figure C-2. Identified hydrothermal and undiscovered hydrothermal supply curves. Available new capacity by overnight capital cost (top) and levelized cost of electricity (bottom) for the Business-as-Usual, Improved Regulatory Timeline, and Technology Improvement *GeoVision* analysis scenarios.

Figure Note: Identified hydrothermal capital costs are competitive for high-temperature resources, but they increase quickly as the resource temperature drops. This “hockey stick” shape is a characteristic shared by many geothermal supply curves due to the abundance of small, low-temperature resources at the tail of the curve. The low temperatures lead to reduced power-generation potential and increased drilling costs relative to the amount of power generated per well.

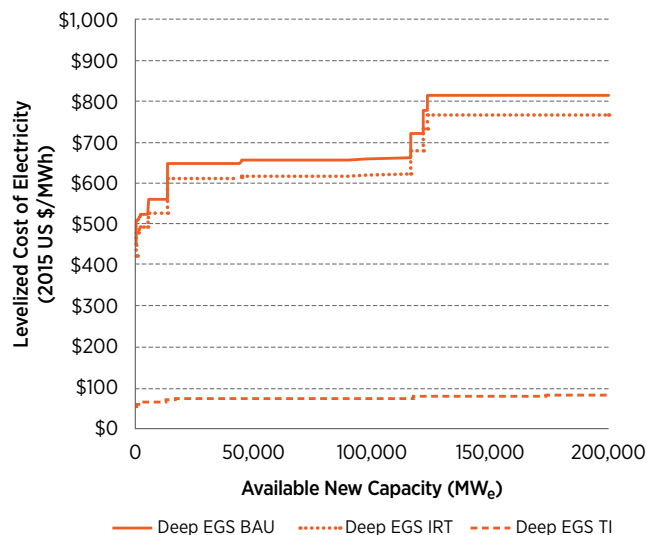
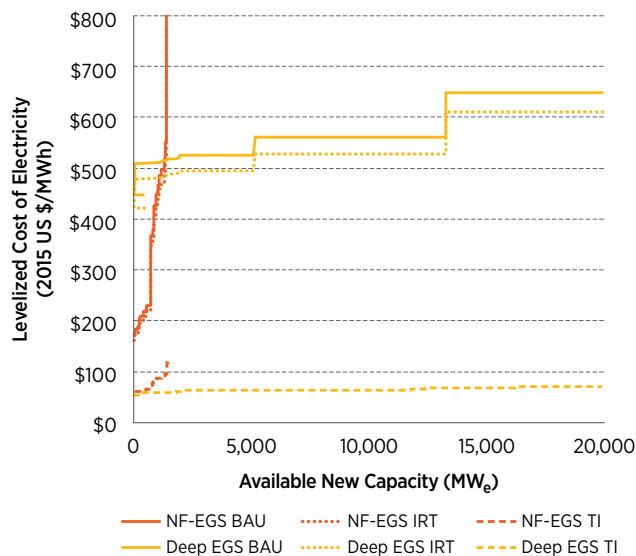
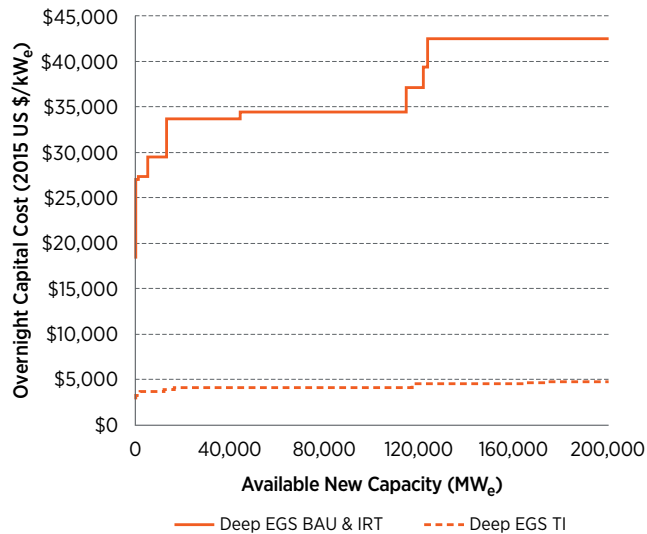
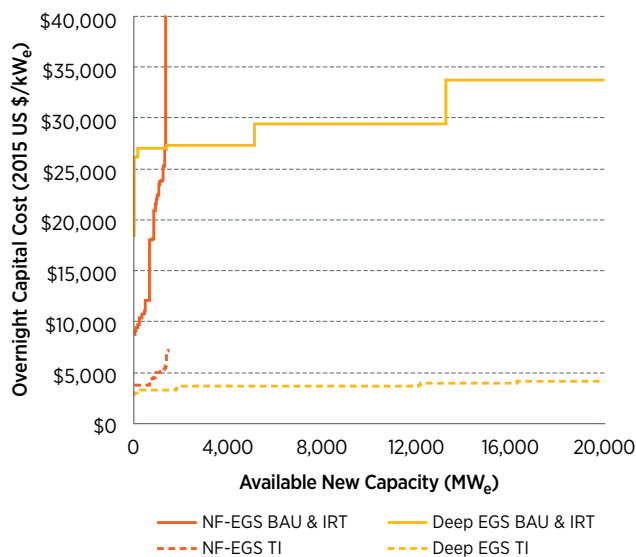


Figure C-3. Near-field enhanced geothermal system and deep enhanced geothermal system supply curves. Available new capacity by overnight capital cost (top) and levelized cost of electricity (bottom) for the Business-as-Usual, Improved Regulatory Timeline, and Technology Improvement *GeoVision* analysis scenarios.

Figure note: The axis for available capacity has been truncated to make the near-field EGS (NF-EGS) costs readable.

Figure C-4. Deep enhanced geothermal system supply curves. Available new capacity by overnight capital cost (top) and levelized cost of electricity (bottom) for the Business-as-Usual, Improved Regulatory Timeline, and Technology Improvement *GeoVision* analysis scenarios.

Figure note: The axis for available capacity has been truncated. These curves are the same deep-EGS supply curves as those in Figure C-3, but are plotted at larger net-capacity and cost scales.

C.1.3 Regional Energy Deployment System Model—Additional Inputs and Assumptions

The ReEDS model (National Renewable Energy Laboratory [NREL] 2018a) is a capacity expansion and dispatch model for the contiguous U.S. electric-power sector. The model relies on system-wide, least-cost

optimization to estimate the type and location of future generation and transmission capacity. To represent the competition among the many electricity generation, storage, and transmission options throughout the contiguous United States, ReEDS identifies the cost-optimal mix of technologies that meet regional electric-power demand based on grid reliability (reserve) requirements, technology resource constraints, and existing policy constraints, such as

state renewable portfolio standards. ReEDS performs this cost minimization for each of 21 two-year periods from 2010–2050. Some of the major outputs of ReEDS include the amount and location of generator capacity and annual generation from each technology, storage capacity expansion, transmission capacity expansion, total electric-sector costs, electricity price, fuel demand and prices, and carbon dioxide (CO₂) emissions.

Within ReEDS, load is served and power plants are constructed in 134 model BAAs that overlay the contiguous United States (Figure C-5). The model BAAs are not designed to represent or align perfectly with real BAAs; instead, they represent model nodes where electricity supply and demand are balanced. The ReEDS transmission network connects those BAAs and comprises roughly 300 representative lines across the three asynchronous interconnections: the Western Interconnection, Eastern Interconnection, and Electric Reliability Council of Texas. The BAAs also respect state boundaries, allowing the model to represent individual state regulations and incentives. The BAAs are further subdivided into 356 resource regions to describe wind

and solar resource supply and quantity with more spatial granularity than allowed by the BAA regions alone. Additional geographical layers include three electricity interconnects, 18 model regional transmission operators designed after existing regional transmission operators, 19 North American Electric Reliability Corporation reliability subregions, and nine census divisions, as defined by the U.S. Census Bureau.

In ReEDS, load is served and operational reliability is maintained over 17 time slices in each model year. Each of the four seasons is modeled as a representative day of four time slices: overnight, morning, afternoon, and evening. The 17th time slice is a summer “superpeak” representing the top 40 hours of summer load. This schedule allows the model to capture seasonal and diurnal variations in demand, wind, and solar profiles. However, the schedule is insufficient to address some of the shorter timescale challenges associated with unit commitment and economic dispatch, especially under scenarios with high penetration of variable renewable generation. To more accurately represent how grid integration of renewable generation might

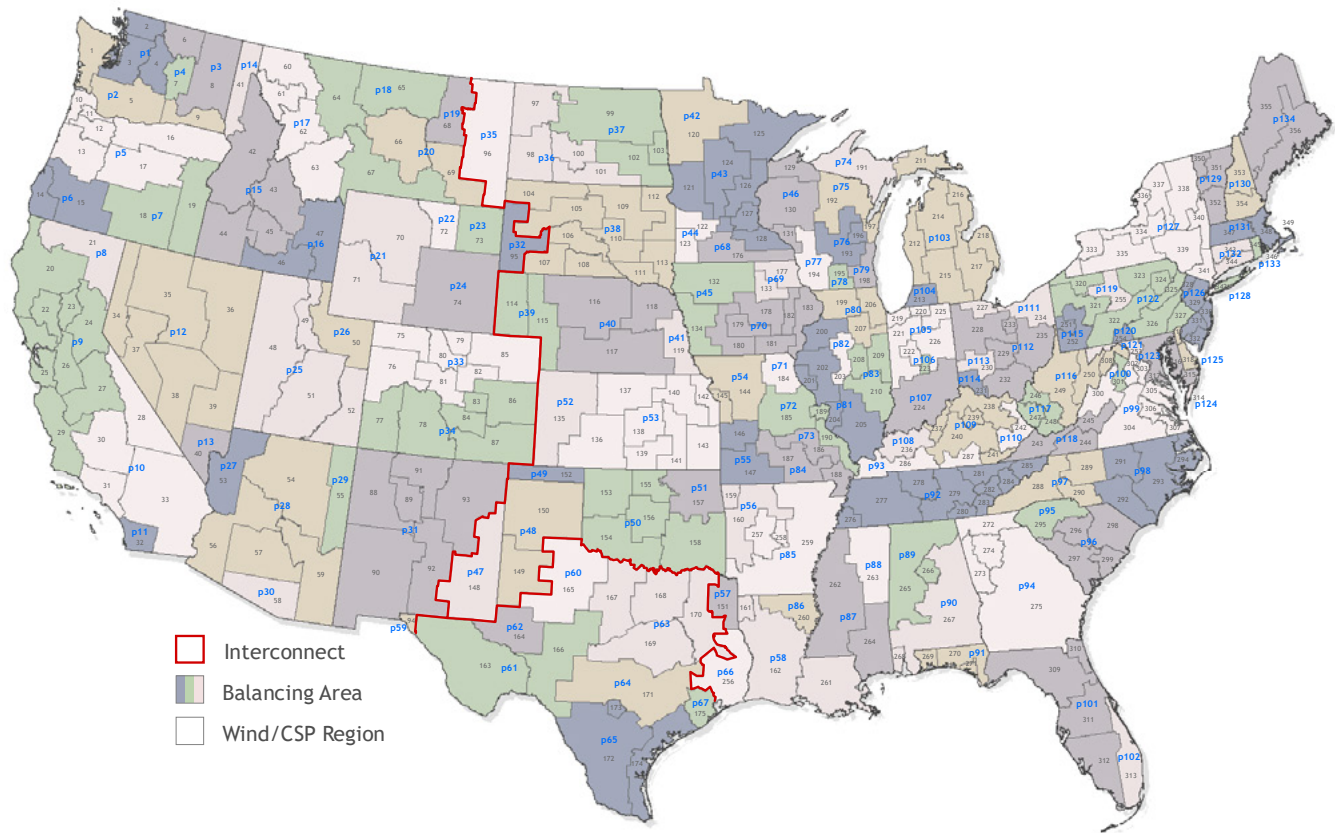


Figure C-5. Map showing the Regional Energy Deployment System regional structure

Figure Note: ReEDS includes three interconnections, 134 model BAAs, and 356 wind and concentrating solar power resource regions.

affect investment and dispatch decisions, the ReEDS model includes statistical parameters designed to address intra-time-slice variability and the generation variability of wind and some other renewable resources. The major conventional thermal-generating technologies represented in ReEDS include simple and combined-cycle natural gas, several varieties of coal, oil/gas steam, and nuclear. In addition to representing these technologies, ReEDS includes many renewable technologies using several kinds of resources, including geothermal, hydropower, biopower, wind, and solar. Electricity storage technologies in the model include pumped hydropower storage, compressed-air energy storage, batteries, and concentrating solar power with thermal storage.

ReEDS is structured as a sequence of 21 individual but interacting optimization problems, each representing a two-year period from 2010–2050. Each ReEDS scenario launches with an infrastructure base representing installed generation and transmission capacity as of December 31, 2010. New infrastructure that came online from 2011 through the present is prescribed into the ReEDS system in the proper model year, and recently decommissioned units are removed in the same way. Similarly, high-likelihood, pending generators are included as prescribed builds in near-term future years, and scheduled retirements are set to be removed from the fleet, as appropriate. Additionally, ReEDS inputs include an equipment lifetime for each technology as a means to retire capacity as it ages. In certain scenarios, some existing stock might be underused because of, for example, high fuel prices or emissions standards. ReEDS facilitates “economic” retirements of underused coal capacity if usage (i.e., capacity factor) falls below a certain threshold. Economic coal retirement in ReEDS is applied starting in 2022 with an increasingly stringent threshold of underuse through 2040.

ReEDS tracks emissions of CO₂, sulfur dioxide (SO₂), nitrogen oxides (NO_x), and mercury from both generators and storage technologies. Annual electric loads and fuel-price supply curves are exogenously specified to define the system boundaries for each period of the optimization. The source for most load and fuel inputs is the EIA’s *Annual Energy Outlook* (AEO). Coal and uranium fuels are assumed to be price inelastic; prices for coal and uranium do not change in

the model no matter how much of those fuels ReEDS uses for optimization. However, natural-gas prices are defined by regional supply curves and respond to changes in electric-sector demand for gas.

C.1.3.1 General Regional Energy Deployment System Model Inputs and Assumptions

ReEDS models future capacity installations on grids for the contiguous United States based on projections of electricity demand and the cost of developing new generation capacity within and among regions. ReEDS is an optimization routine, and it selects capacity additions among the available electricity-generating technologies that minimize system costs within the model constraints and requirements based on the technology and fuel costs provided by the user. For the *GeoVision* analysis, the Annual Technology Baseline (ATB) (NREL 2018b) was used to provide detailed cost and performance data (both current and projected) for non-geothermal renewable and conventional technologies. The ATB is a set of input assumptions updated annually by NREL to support and inform electric-sector analysis in the United States. The products of this work include assessments of current and projected technology cost and performance through 2050 for renewable and conventional electricity-generation technologies. The ATB includes Low, Mid, and High technology-cost projections for renewable energy technology costs and performance based on values reported in public literature. The *GeoVision* analysis used the 2016¹¹⁰ version of the ATB (Cole et al. 2016b, NREL 2016) and assumes the Mid-case scenario technology cost projections.

ReEDS also requires projections of electricity demand and fuel prices. The National Renewable Energy Laboratory (NREL) annually documents a diverse set of potential futures of the U.S. electricity sector that includes technology cost and performance assumptions from the ATB. These potential futures are called the *Standard Scenarios*. The Standard Scenarios comprise a range of power-sector scenarios that provide quantitative examination of how ranges of values of specific inputs impact the development of the power sector (NREL 2018b). The *GeoVision* analysis used the

¹¹⁰ The 2016 versions of the ATB and Standard Scenarios were the most recent data available at the time this analysis was performed. The 2018 ATB has since been published and uses lower cost projections for some technologies (notably wind and solar technologies) than the 2016 ATB. Using the updated cost projections would make wind and solar technologies—and perhaps others—more competitive, likely resulting in lower geothermal deployment projections than those presented in this report. See Section C.1.5 for more information.

2016 version of the Standard Scenarios (Cole et al. 2016a) and assumes the NREL Mid-case scenario for all modeling runs, unless otherwise noted. The Mid-case scenario is used in the Standard Scenario analysis as a reference case reflecting business-as-usual conditions. The default assumptions used in the Mid-case scenario reflect median or midline expectations for model inputs (e.g., Reference-case fuel prices, Mid-case technology costs) based on current information. The Mid-case scenario is used in the *GeoVision* analysis for the same purpose—to represent present and future costs of non-geothermal technologies. The Mid-case scenario uses the following assumptions:

- Electricity demand growth: AEO 2016 Reference case (EIA 2016b) (Figure C-6)
- Fuel prices: AEO 2016 Reference case (EIA 2016b) (Figure C-7)
- Existing fleet retirement: lifetime retirements based on ABB Ability™ Velocity Suite database (ABB 2016)
- Policy/regulatory environment: includes federal and state policies enacted as of April 1, 2016, with the exception of the federal Clean Power Plan. The Clean Power Plan was not assumed to be in effect in the *GeoVision* analysis ReEDS runs.

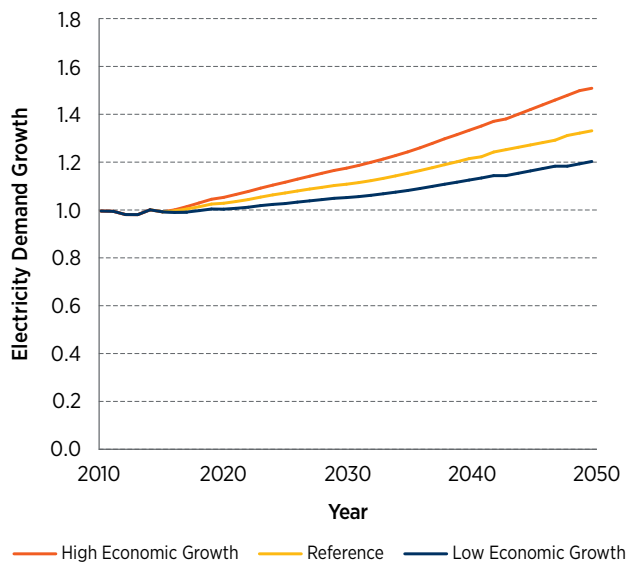


Figure C-6. Demand growth trajectories relative to 2010 demand from the Energy Information Administration (2016b)

Figure Note: The Standard Scenario Mid-Case used in the *GeoVision* analysis assumes the Reference demand growth curve.

Non-geothermal electricity-generation technology costs assume the 2016 ATB Mid-case projections. Mid-case projections for the major electricity-generation technologies in ReEDS are shown for current (2015) and projected future (2030 and 2050) years in Table C-3 and Table C-4, respectively.

Major financing assumptions in ReEDS for all non-geothermal electricity-generation technologies are shown in Table C-5.

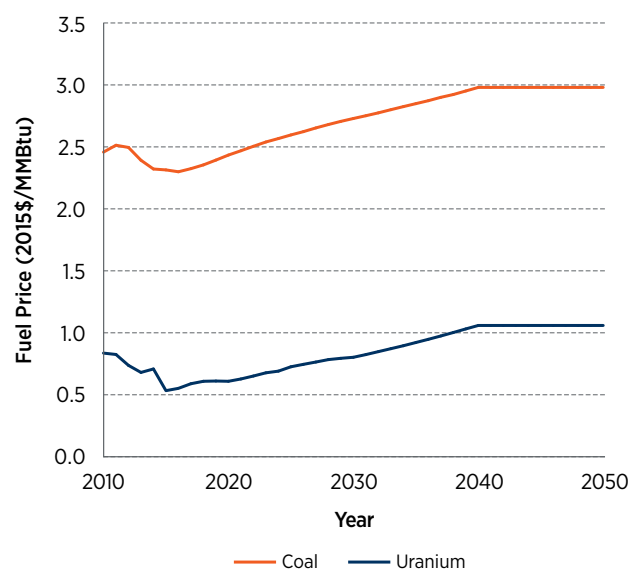
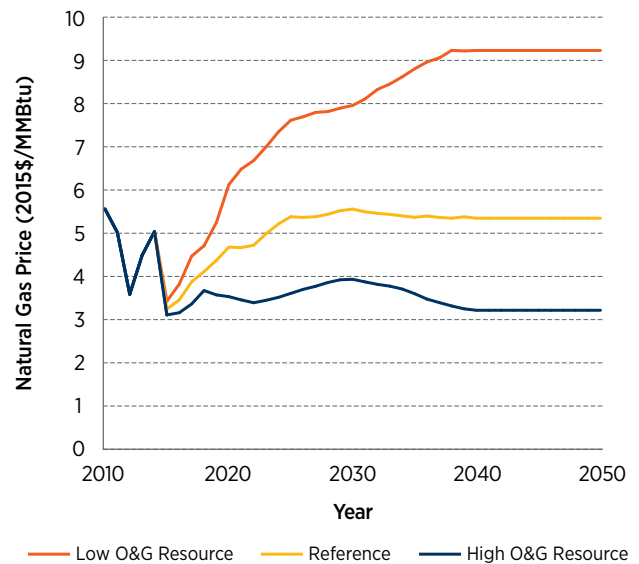


Figure C-7. Fuel price trajectories from the Energy Information Administration (2016b)

Figure Note: The Standard Scenario Mid-Case used in the *GeoVision* analysis assumes the Reference natural-gas price curve.

Technology		CF Range		CAPEX Range		Fuel Costs (\$/MWh _e)	Fixed O&M (\$/kW _e /yr)	Variable O&M (\$/MWh _e)	LCOE Range	
		Low (%)	High (%)	Low (\$/kW _e)	High (\$/kW _e)				Low (\$/MWh _e)	High (\$/MWh _e)
2015										
Coal	PC	61%	85%	\$4,103	\$4,103	\$19	\$32	\$5	\$89	\$115
	IGCC	61%	85%	\$4,403	\$4,403	\$18	\$52	\$7	\$98	\$126
	IGCC-CCS	61%	85%	\$7,595	\$7,595	\$21	\$74	\$9	\$153	\$201
Gas	CT	5%	30%	\$869	\$869	\$32	\$7	\$13	\$85	\$292
	CC	48%	87%	\$1,056	\$1,056	\$22	\$14	\$3	\$42	\$55
	CC-CCS	48%	87%	\$2,198	\$2,198	\$24	\$32	\$7	\$66	\$95
Nuclear		92%	92%	\$6,369	\$6,369	\$6	\$95	\$2	\$104	\$104
Biopower		52%	52%	\$3,991	\$3,991	\$3	\$5	\$3	\$150	\$150
Geothermal		80%	90%	\$5,049	\$13,464	\$0	\$155	\$0	\$78	\$225
CSP with 10-hr TES		42%	59%	\$7,915	\$7,915	\$0	\$64	\$4	\$160	\$223
2030										
Coal	PC	61%	85%	\$3,941	\$3,941	\$20	\$32	\$5	\$87	\$112
	IGCC	61%	85%	\$4,080	\$4,080	\$17	\$52	\$7	\$92	\$119
	IGCC-CCS	61%	85%	\$6,821	\$6,821	\$19	\$74	\$9	\$139	\$183
Gas	CT	5%	30%	\$805	\$805	\$53	\$7	\$13	\$102	\$295
	CC	48%	87%	\$983	\$983	\$36	\$14	\$3	\$56	\$68
	CC-CCS	48%	87%	\$1,930	\$1,930	\$41	\$32	\$7	\$80	\$105
Nuclear		92%	92%	\$6,098	\$6,098	\$8	\$95	\$2	\$103	\$103
Biopower		52%	52%	\$3,750	\$3,750	\$3	\$5	\$3	\$145	\$145
Geothermal		80%	90%	\$5,049	\$13,464	\$0	\$155	\$0	\$78	\$225
CSP with 10-hr TES		42%	59%	\$3,671	\$3,671	\$0	\$40	\$4	\$78	\$109
2050										
Coal	PC	61%	85%	\$3,737	\$3,737	\$21	\$32	\$5	\$85	\$109
	IGCC	61%	85%	\$3,700	\$3,700	\$18	\$52	\$7	\$87	\$12
	IGCC-CCS	61%	85%	\$5,977	\$5,977	\$20	\$74	\$9	\$127	\$166
Gas	CT	5%	30%	\$744	\$744	\$51	\$7	\$13	\$98	\$277
	CC	48%	87%	\$913	\$913	\$35	\$14	\$3	\$53	\$65
	CC-CCS	48%	87%	\$1,643	\$1,643	\$40	\$32	\$7	\$74	\$96
Nuclear		92%	92%	\$5,422	\$5,422	\$11	\$95	\$2	\$97	\$98
Biopower		52%	52%	\$3,452	\$3,452	\$3	\$5	\$3	\$139	\$139
Geothermal		80%	90%	\$5,049	\$13,464	\$0	\$155	\$0	\$78	\$225
CSP with 10-hr TES		42%	59%	\$3,671	\$3,671	\$0	\$40	\$4	\$78	\$109

Table C-3. Dispatchable Electricity-Generation Technology Cost and Performance Data from the 2016 Annual Technology Baseline Mid-case Scenario by Generation Technology

Table Note: CF=capacity factor, CAPEX=capital expenditure, O&M=operations and maintenance, LCOE=levelized cost of electricity, PC=pulverized coal, IGCC=integrated gasification combined cycle, CCS=carbon capture and storage; CT=combustion turbine, CC=combined cycle, CSP=concentrating solar power, TES=thermal energy storage (NREL 2016).

Technology		CF Range		CAPEX Range		Fuel Costs (\$/MWh _e)	Fixed O&M (\$/ kW _e /yr)	Variable O&M (\$/MWh _e)	LCOE Range	
		Low (%)	High (%)	Low (\$/kW _e)	High (\$/kW _e)				Low (\$/MWh _e)	High (\$/MWh _e)
2015										
Wind	Land-Based	13%	52%	\$1,723	\$2,186	\$0	\$51	\$0	\$47	\$228
	Offshore	34%	49%	\$5,739	\$7,344	\$0	\$148	\$0	\$162	\$223
Photovoltaic	Utility	14%	28%	\$1,942	\$1,942	\$0	\$16	\$0	\$81	\$162
	Commercial	11%	19%	\$2,249	\$2,249	\$0	\$14	\$0	\$137	\$225
	Residential	13%	21%	\$3,096	\$3,096	\$0	\$18	\$0	\$170	\$282
Hydropower		60%	66%	\$3,895	\$7,261	\$0	\$77	\$0	\$90	\$162
2030										
Wind	Land-Based	17%	56%	\$1,567	\$2,578	\$0	\$49	\$0	\$40	\$194
	Offshore	37%	54%	\$4,321	\$5,501	\$0	\$115	\$0	\$112	\$154
Photovoltaic	Utility	14%	28%	\$1,041	\$1,041	\$0	\$8	\$0	\$43	\$86
	Commercial	11%	19%	\$1,270	\$1,270	\$0	\$8	\$0	\$77	\$127
	Residential	13%	21%	\$1,487	\$1,487	\$0	\$10	\$0	\$82	\$137
Hydropower		60%	66%	\$3,895	\$6,996	\$0	\$77	\$0	\$90	\$156
2050										
Wind	Land-Based	18%	59%	\$1,558	\$2,618	\$0	\$46	\$0	\$37	\$180
	Offshore	38%	55%	\$4,087	\$5,196	\$0	\$112	\$0	\$104	\$143
Photovoltaic	Utility	14%	28%	\$852	\$852	\$0	\$8	\$0	\$36	\$72
	Commercial	11%	19%	\$988	\$988	\$0	\$8	\$0	\$61	\$100
	Residential	13%	21%	\$1,194	\$1,194	\$0	\$10	\$0	\$67	\$111
Hydropower		60%	66%	\$3,895	\$6,646	\$0	\$77	\$0	\$90	\$150

Table C-4. Non-Dispatchable Electricity-Generation Technology Cost and Performance Data from the 2016 Annual Technology Baseline Mid-case Scenario by Generation Technology

Table Note: CF=capacity factor, CAPEX=capital expenditure, O&M=operations and maintenance, LCOE=levelized cost of electricity (NREL 2016).

Type of Assumption	Value Used
Evaluation period	20 years
Inflation rate	2.5%
Interest rate—nominal	8%
Rate of return on equity—nominal	13%
Debt fraction	60%
Combined state and federal tax	40%
Discount rate—nominal (real)	8.1% (5.4%)
Modified accelerated cost recovery system (non-hydropower renewables)	5 years
Modified accelerated cost recovery system (nuclear, combustion turbines)	15 years
Modified accelerated cost recovery system (other fossil, hydropower, storage)	20 years

Table C-5. Major Financial Assumptions from the 2016 Annual Technology Baseline for Non-Geothermal Electricity-Generation Technologies used in the Regional Energy Deployment System Model for the *GeoVision* Analysis

C.1.4 Supplemental Modeling Results

This section provides results from the ReEDS model for the *GeoVision* analysis scenarios. The following projections through 2050 are presented for each scenario:

- Capacity-deployment projections by geothermal resource type
- Total electric-sector capacity deployment projections for all technologies
- Total electric-sector generation projections for all technologies.

C.1.4.1 Business-as-Usual Scenario

Figure C-8 illustrates the installed geothermal capacity by year for the *GeoVision* analysis BAU scenario. The results of this scenario show that—absent any substantial changes to the industry—geothermal will continue to be a niche player in the electricity-generation market, with capacity additions confined to the western United States. Most new geothermal capacity additions come from undiscovered hydrothermal resources (Figure C-8), indicating that the exploration and discovery of new

geothermal resources is key to additional conventional hydrothermal deployment. In the BAU scenario, EGS technologies are too costly to be competitive so none are deployed within the ReEDS model. Figure C-9 illustrates the cumulative installed capacity by year for all technologies in ReEDS under BAU, and Figure C-10 illustrates annual electricity generation by year for all technologies.

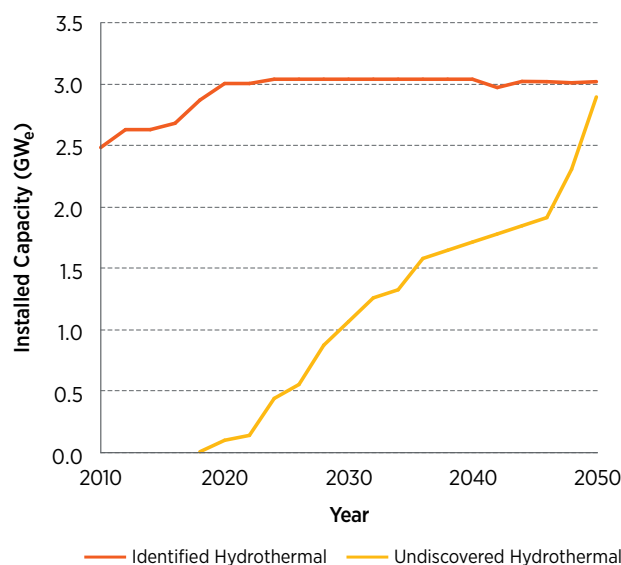


Figure C-8. Installed geothermal capacity by year for the Business-as-Usual scenario

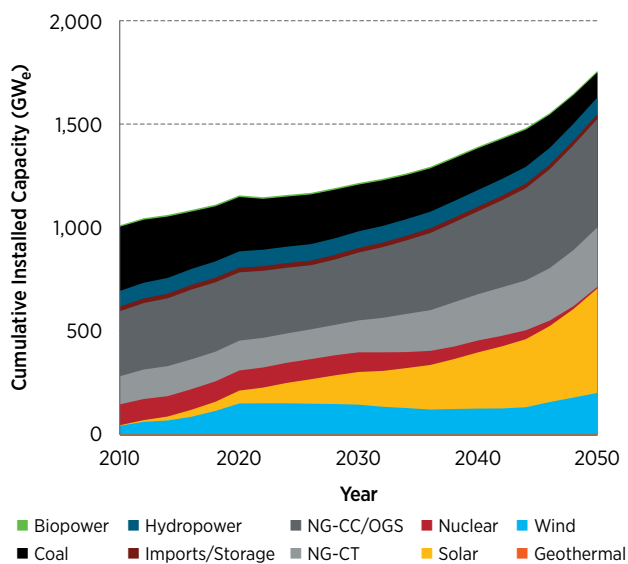


Figure C-9. Cumulative installed capacity by year for all technologies in the Regional Energy Deployment System for the Business-as-Usual scenario

Figure Note: NG-CC=Natural Gas Combined Cycle; OGS=Oil/Gas Steam Turbine; NG-CT=Natural Gas Combustion Turbine

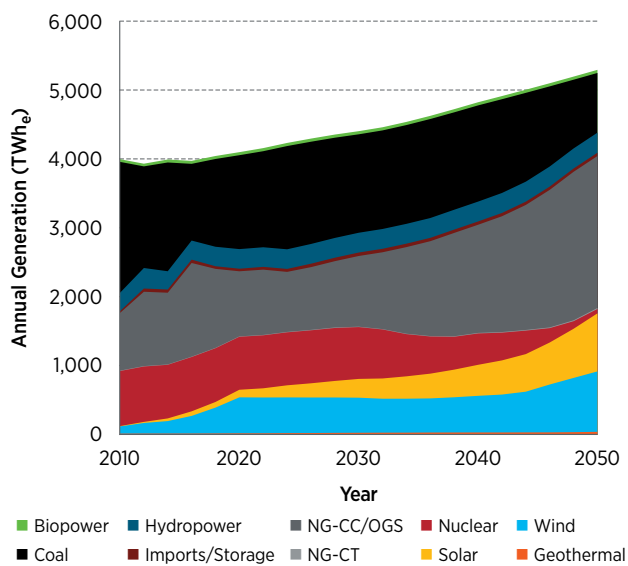


Figure C-10. Annual electricity generation by year for all technologies in the Regional Energy Deployment System for the Business-as-Usual scenario

C.1.4.2 Improved Regulatory Timeline Scenario

The *GeoVision* analysis IRT scenario results indicate that the geothermal industry could double in size through regulation reform alone (Figure C-11). Reducing construction timelines has big impacts on overall project costs and subsequent deployment absent any technology advances, meaning that hydrothermal resources could show significantly more deployment even with current technology if soft costs and barriers are reduced. As in the BAU scenario, most of the new geothermal capacity additions come from undiscovered hydrothermal resources, illustrating that the exploration and discovery of new geothermal resources remain key to additional conventional hydrothermal deployment. EGS technologies remain too costly to be deployed in the IRT scenario, despite the shorter assumed construction timeline. Figure C-12 shows cumulative installed capacity by year for all technologies in ReEDS for the IRT scenario, and Figure C-13 shows annual electricity generation by year for all technologies in ReEDS for the IRT scenario.

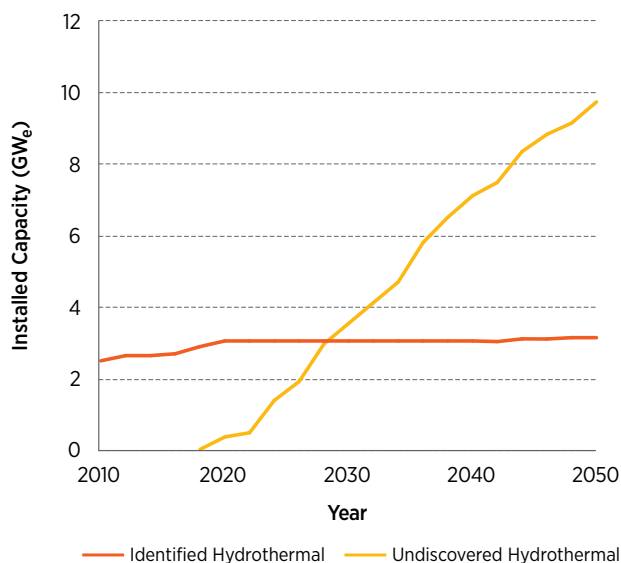


Figure C-11. Installed geothermal capacity by year for the Improved Regulatory Timeline scenario

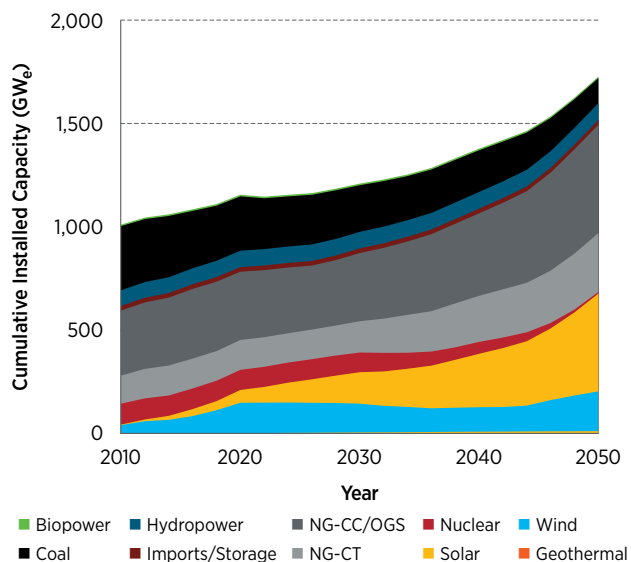


Figure C-12. Cumulative installed capacity by year for all technologies in the Regional Energy Deployment System for the Improved Regulatory Timeline scenario

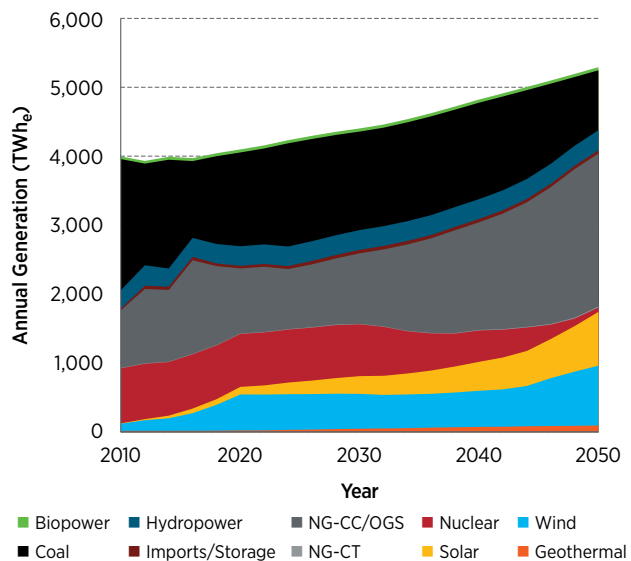


Figure C-13. Annual electricity generation by year for all technologies in the Regional Energy Deployment System for the Improved Regulatory Timeline scenario

C.1.4.3 Technology Improvement Scenario

The results of the *GeoVision* analysis TI scenario indicate that EGS can achieve notable deployment rates if there are significant technology improvements and related reductions in capital cost and risk (Figure C-14). Because of its high capacity factor, generation from a specific amount of installed geothermal capacity is higher than generation from an equivalent amount of installed capacity of other renewables. In the TI scenario, geothermal can supply 8.5% of all U.S. electricity-generation demand in 2050 from only 61 GW of installed capacity. The majority of this (43.6 GW) is from EGS deployments. These deployments do not become commercially available until 2030, but then the technology is rapidly deployed, with installed capacity steadily increasing through 2050. A significant portion of geothermal capacity comes from undiscovered hydrothermal resources as well, reaching 12.6 GW of installed capacity by 2050. This again underscores the findings from the other *GeoVision* analysis scenarios that the exploration and discovery of new geothermal resources are key to increasing conventional hydrothermal deployment. In the TI scenario, hydrothermal technologies also benefit from technology advances and lower costs, resulting in higher installed hydrothermal capacity than in the IRT scenario—even with the added competition from EGS. Figure C-15 shows cumulative installed capacity by year for all technologies in ReEDS for the TI scenario, and Figure C-16 shows annual electricity generation by year for all technologies in the ReEDS for the TI scenario.

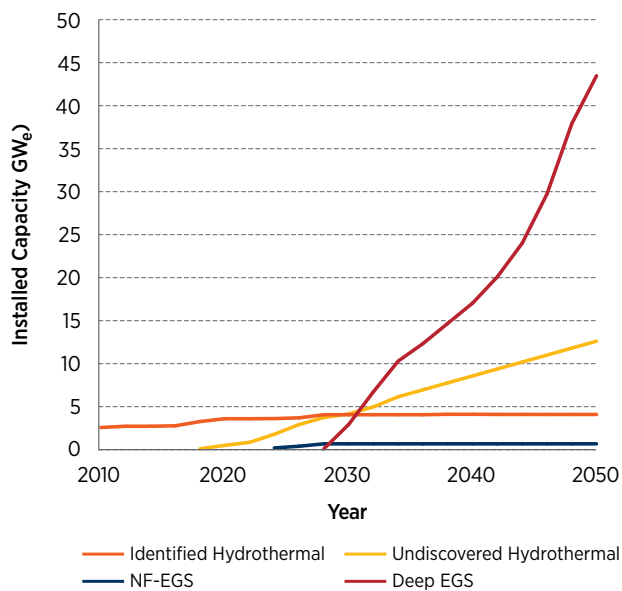


Figure C-14. Installed geothermal capacity by year for the Technology Improvement scenario

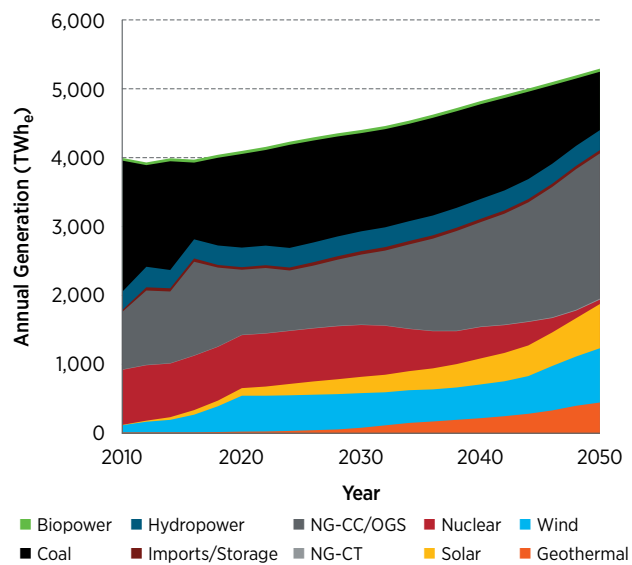


Figure C-16. Annual electricity generation by year for all technologies in the Regional Energy Deployment System for the Technology Improvement scenario

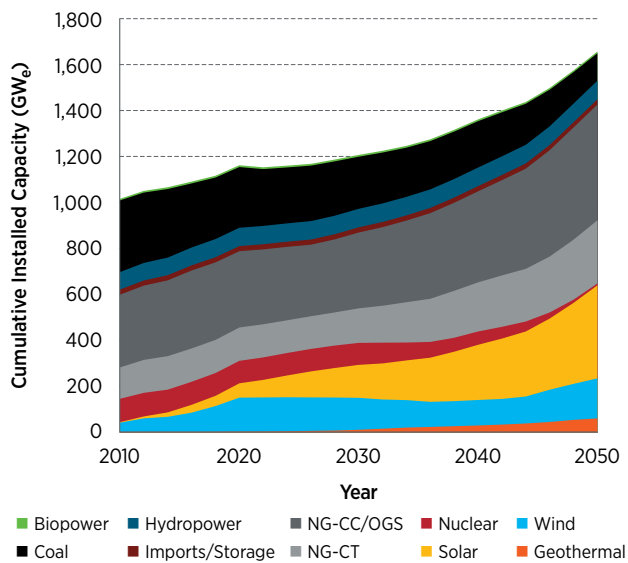


Figure C-15. Cumulative installed capacity by year for all technologies in the Regional Energy Deployment System for the Technology Improvement scenario

C.1.4.4 Standard Scenario Results

The ReEDS Standard Scenarios were run using the assumptions for the *GeoVision* analysis TI scenario for geothermal technologies. As discussed in Section

C.1.3.1, the Standard Scenarios are a set of power-sector scenarios that provide a quantitative examination of how ranges of values of specific inputs impact power-sector development; these scenarios are described in detail in Cole et al. 2016a. The scenarios capture a reasonable breadth of trajectories of costs, performance, policy, and other drivers; thus, they enable assessment of a range of potential futures rather than a single, mid-case outlook. The *GeoVision* analysis assumes the Mid-case scenario for the core BAU, IRT, and TI scenarios. The main body of the report also includes discussion of the High Natural-Gas Prices scenario (Table C-6) to illustrate the potential of geothermal technologies under alternative future scenarios. The Standard Scenarios look at the sensitivity of the ReEDS model results to seven areas:

1. Electricity demand growth
2. Fuel prices
3. Electricity-generation technology costs
4. Existing fleet retirements
5. Policy/regulatory environment
6. Earth system feedbacks
7. Resource and system constraints.

Table C-6 summarizes the Standard Scenarios used for the *GeoVision* analysis sensitivity scenarios.

Group	Scenario	Notes
Electricity Demand Growth	Reference Demand Growth	AEO 2016 Reference
	Low Demand Growth	AEO 2016 Low Economic Growth
	High Demand Growth	AEO 2016 High Economic Growth
	Vehicle Electrification	Plug-in electric vehicle/plug-in hybrid electric vehicle adoption reaches 40% of sales by 2050; 45% of charging utility-controlled, 55% opportunistic
Fuel Prices	Reference Natural Gas Prices	AEO 2016 Reference
	Low Natural Gas Prices	AEO 2016 High Oil and Gas Resource and Technology
	High Natural Gas Prices	AEO 2016 Low Oil and Gas Resource and Technology
Electricity-Generation Technology Costs	Mid-Case Technology Cost	2016 ATB Mid-Case Projections
	Low RE Cost	2016 ATB Renewable Energy Low-Case Projections
	High RE Cost	2016 ATB Renewable Energy High-Case Projections
	Nuclear Technology Breakthrough	50% reduction in nuclear capital costs over all years
Existing Fleet Retirements	Reference Retirement	Lifetime retirements based on ABB Velocity Suite database (ABB 2016)
	Extended Nuclear Lifetime	Relicensing to 80 years
	Accelerated Coal Retirement	Coal power-plant lifetimes reduced by 10 years
Policy/Regulatory Environment	Current Law	Includes policies as of April 1, 2016. (Does not include a Clean Power Plan for GeoVision)
	Extended Incentives for RE Generation	Extend investment tax credit/production tax credit through 2030 for eligible technologies
Earth System Feedbacks	No Climate Feedback	No feedback because of changes in the climate
	Impacts of Climate Change	Impact of higher temperatures on generators, transmission, and demand; derived from IGSM-CAM climate scenario
Resource and System Constraints	Default Resource Constraints	Used for the Mid-Case Scenario
	Reduced RE Resource	25% cut to each resource in input supply curves
	Barriers to Transmission System Expansion	Expansion three times transmission capital cost; no new AC-DC-AC interties; two times transmission loss factors
	Restricted Cooling Water Use	New construction may not use fresh water for cooling

Table C-6. Summary of the Standard Scenarios

Source: Cole et al. 2016a

Table Notes: Scenarios in bold indicate assumptions used in the mid-case scenario (default assumptions). RE = renewable energy, IGSM-CAM = Integrated Global System Model-Community Atmosphere Model.

Results of all Standard Scenarios using the *GeoVision* analysis TI scenario are shown in Figure C-17. The scenarios using the *GeoVision* analysis TI inputs for geothermal technologies can be divided into three groups as described in the subsequent paragraphs.

The first group comprises scenarios where the amount of installed geothermal capacity is significantly higher than in the Mid-case scenario, consisting of the High Natural Gas Prices and High RE Cost Standard Scenarios. The High Natural Gas Prices scenario (see Figure C-7 for assumed natural-gas prices in this scenario) results in the most installed geothermal capacity, with 118 GWe by 2050, followed closely by the High RE Cost scenario, with 107 GWe. These scenarios show that geothermal deployment in the TI scenario can be double what it is in the Mid-case scenario in futures where the costs of competing electricity-generation technologies (e.g., natural gas, other renewables) are high. Because of the high capacity factor of geothermal power plants, geothermal accounts for about 16% of total U.S. electricity generation in 2050 for the High Natural-Gas Prices scenario. For both of these high geothermal-penetration

scenarios, the additional installed geothermal capacity compared to the TI case is made up almost entirely of deep-EGS resources.

The second group comprises scenarios where the amount of installed geothermal capacity is significantly less than in the Mid-case scenario. Only the Low RE Cost scenario fits in this group. When lower-cost renewable energy generation is assumed, geothermal installed capacity drops to about 20 GWe—or less than one-third of the value in the Mid-case scenario. In this scenario, geothermal deployment is replaced by lower-cost renewable energy options.

The third group comprises scenarios where the impact on geothermal deployment does not vary significantly from the Mid-case scenario. The rest of the scenarios fit in this group. For the majority of the scenarios, the potential scenario conditions do not significantly favor or hinder geothermal deployment compared to the Mid-case scenario; the resulting installed geothermal capacity is within +5 GWe to (-20) GWe of the Mid-case scenario.

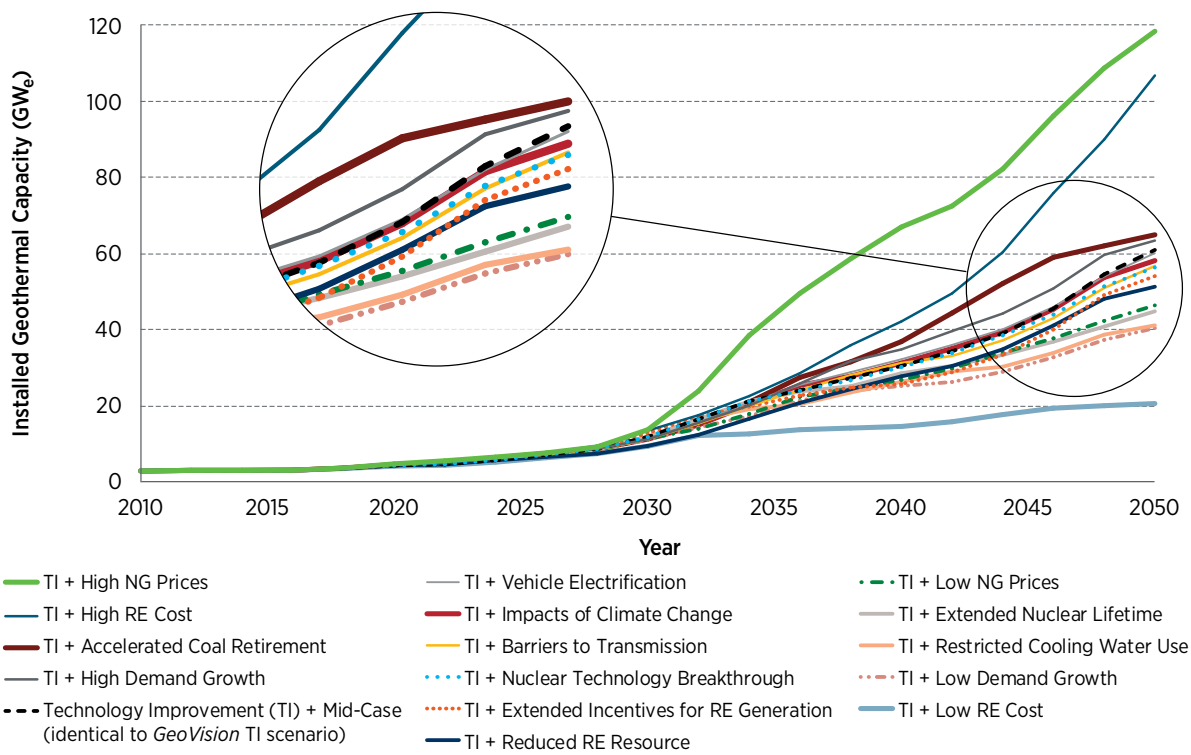


Figure C-17. Total installed geothermal capacity for the ReEDS Standard Scenarios assuming the *GeoVision* Technology Improvement case

Figure Note: The Standard Scenarios are listed in the legend in order of total installed capacity in 2050, from highest to lowest.

C.1.5 Discussion

Figure C-18 shows the electric-sector installed capacity for all technologies projections for the EIA's AEO 2016 Reference case. The technologies have been grouped to match the categories from ReEDS results to facilitate comparisons between the AEO 2016 Reference case and the *GeoVision* analysis BAU scenario (Figure C-12). The AEO's projected 7.2 GW_e installed geothermal capacity for 2040 is more optimistic than the 4.8 GW_e value in 2040 (5.9 GW_e in 2050) from the *GeoVision* analysis BAU scenario (note that both the EIA and BAU values are small enough compared to overall installed electric-generation capacity to not have much impact overall). The largest discrepancy, on a percentage basis, is the difference in nuclear installed capacity. This difference is due to exogenous assumptions about nuclear lifetimes rather than the relative competitiveness of nuclear plants with other generation technologies.¹¹¹ AEO 2016 assumes that all nuclear plants will receive a second relicense and therefore have an 80-year lifetime, resulting in 99 GW_e of installed capacity through 2040. The *GeoVision* BAU scenario, however, assumes a single relicense, giving nuclear plants a fixed 60-year lifetime. The result is that nuclear capacity drops from around 100 GW_e at the start of the model run in 2010 to 57 GW_e by 2040 and 8 GW_e by 2050.

There are also variations in capacity projections for other technologies. For instance, AEO 2016 projects more coal plant retirements. The AEO 2016 Reference case shows about 170 GW_e of installed coal capacity in 2040, whereas under the *GeoVision* analysis BAU scenario, the installed capacity of coal technologies falls to about 200 GW_e by 2040 and 120 GW_e by 2050. Additionally, the *GeoVision* BAU scenario shows substantially more growth in solar capacity, totaling 272 GW_e in 2040 vs. 158 GW_e under the AEO 2016 Reference case. Natural-gas combustion-turbine installed capacity in 2040 is also substantially greater under the *GeoVision* analysis BAU scenario than the AEO 2016: 224 GW_e vs. 142 GW_e, respectively. Natural-gas combined-cycle installed capacity projections are nearly identical between the models, as are installed capacity projections for hydropower.

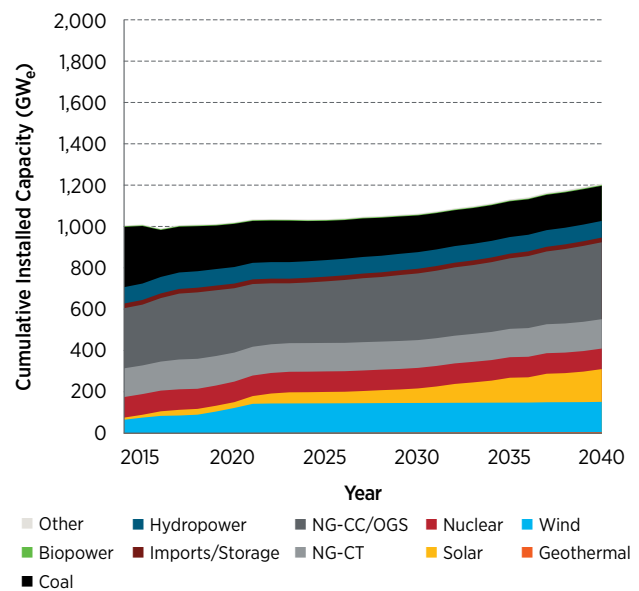


Figure C-18. Cumulative installed capacity through 2040 for electricity-generation technologies projected by 2016 Energy Information Administration Annual Energy Outlook (Reference case)

Figure Note: Technology types have been grouped to match categories from ReEDS results to facilitate comparisons (EIA 2016b)

Despite some quantitative differences, both the *GeoVision* BAU results from ReEDS and the AEO 2016 are in general agreement about the future of the U.S. electric sector. Both project that natural-gas generation and renewable energy technologies such as wind and solar will play an increasingly larger role in the future. This has implications for the *GeoVision* analysis. The ReEDS modeling in the *GeoVision* analysis is based on the 2016 ATB. EIA and NREL have since produced additional AEO and ATB updates (2017 and 2018) with projected natural-gas, wind, and solar electricity-generation costs that have all decreased compared to 2016 projections. Figure C-19 illustrates how natural-gas price projections have dropped from AEO 2016 to AEO 2018. Figure C-20 shows how the projected costs of wind and solar technologies used in the ATB Mid-case scenario have decreased from 2016 to 2018. These changes to the ReEDS inputs would make natural-gas, wind, and solar technologies more competitive and would likely decrease the deployment of geothermal (and other) technologies compared to 2016 values. Identifying the extent of decreases in geothermal

¹¹¹ Both the National Energy Modeling System (used for the AEO) and ReEDS (used for the *GeoVision* analysis) have revised their nuclear retirement criteria and assumptions since the 2016 model version.

capacity additions under the 2018 cost projections was not possible within the scope of the *GeoVision* analysis. However, preliminary ReEDS model runs using 2017 ATB and Standard Scenario inputs (including updated natural-gas prices) indicated that—while geothermal capacity deployments are lower compared to using 2016 data—the general trends of increased geothermal deployment observed for the *GeoVision* scenarios are still valid. The Standard Scenario results shown in Figure C-17 support the resilience of the geothermal deployment results across a range of scenarios. Although updated ReEDS model runs using current cost data would likely reduce overall geothermal deployment numbers, the lessons learned from the *GeoVision* analysis still hold.

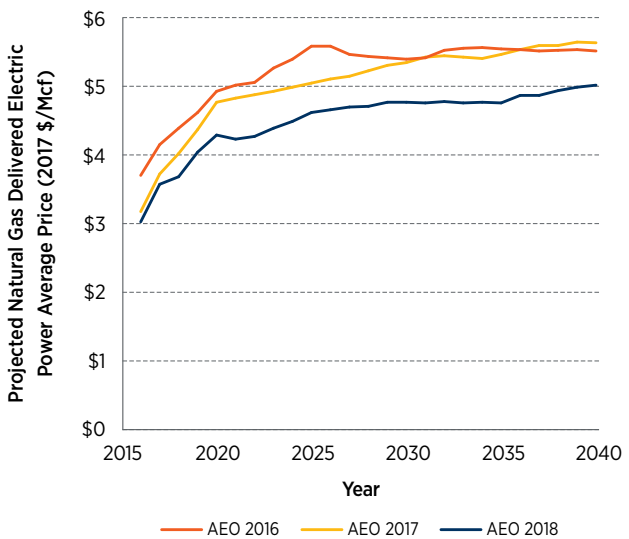


Figure C-19. Comparison of natural-gas delivered electric-power average price (2017\$ per thousand cubic feet [Mcf]) projections from the Annual Energy Outlook 2016, Annual Energy Outlook 2017, and Annual Energy Outlook 2018

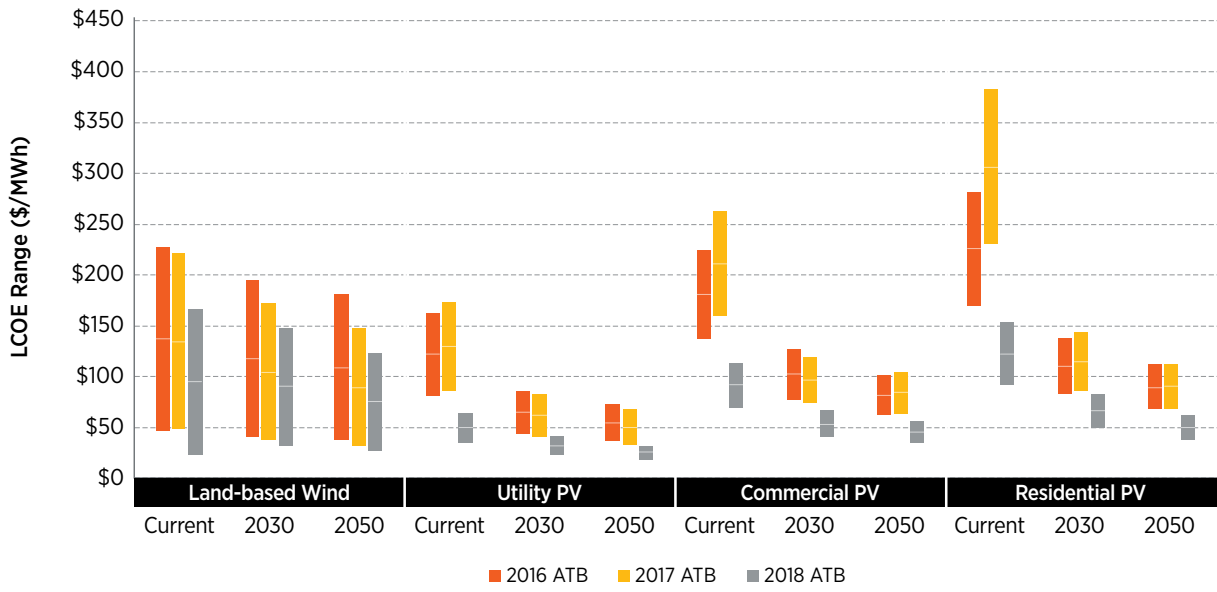


Figure C-20. Levelized cost of electricity ranges used for wind and solar technologies in 2016–2018 Annual Technology Baseline Mid-case scenarios

Source: NREL n.d. (ATB Summary)

C.2 Heating and Cooling Sector: Distributed Geothermal Market Demand (dGeo) Model

As noted in Section 3.1.3, to evaluate the non-electric heating and cooling sector, the U.S. Department of Energy developed a dedicated modeling tool called the Distributed Geothermal Market Demand (dGeo) model. The *GeoVision* analysis uses the dGeo model to evaluate the potential of geothermal heat pump (GHP) and geothermal direct-use district-heating technologies in the non-electric heating and cooling sector. Heating and cooling sector assumptions and inputs for the *GeoVision* analysis are structured around the dGeo model framework described in subsequent paragraphs. District-heating-specific and GHP-specific model inputs and results are also discussed in Sections C.3 and C.4. The information and graphics in Section C.2 are sourced primarily from Gleason et al. 2017.

The dGeo model uses a bottom-up, spatially resolved, agent-based framework to simulate the potential market for geothermal distributed energy resources. A region is modeled as a combination of agents that approximate the actual population of buildings and residences in the region. This framework shares several key traits with classical agent-based modeling, but also has some important differences (see Gleason et al. 2017).

In dGeo, each agent represents a type of commercial or residential building, complete with several key attributes. The dGeo model framework involves six main components:

1. **Agent Generation:** During agent generation, which occurs at model initialization, dGeo creates a synthetic population of agents within each region.
2. **Agent Mutation:** At each time step, agents are updated to inherit new time-dependent attributes (or change existing ones) that may affect their evaluation of the opportunity for technology adoption.
3. **Assessment of Technical Potential:** Based on the status of agents at each time step, dGeo assesses the quantity of district-heating and GHP resource that is technically feasible, given proximity to end-use thermal demand and—in the case of GHP—siting constraints.
4. **Assessment of Economic Potential:** At each time step, dGeo evaluates the economics of an investment in district-heating and GHP technologies for each agent using discounted cash-flow analysis. A similar analysis is performed for the alternative/baseline heating and cooling technology, such as a traditional heating, ventilation, and air-conditioning (HVAC) system, to represent the “competition” for district-heating and GHP technologies. These cash-flow analyses produce financial metrics that can be used to assess how economically attractive each technology is to each agent (relative to the baseline competition), as well as the overall number of agents for whom technology adoption would be economically rational.
5. **Assessment of Market Potential:** Based on empirical data that relate payback period of a given technology to the number of customers who would be willing to adopt a technology, dGeo translates economic potential into market potential at each time step.
6. **Simulation of Technology Deployment:** Finally, at each time step, dGeo simulates technology deployment based on current economic evaluations of each agent, as well as population-level interaction effects from other agents.

dGeo performs simulations beginning with a base year of 2012, and it advances in 2-year time steps through 2050. dGeo can simulate results for the continental United States; Hawaii and Alaska were excluded from the model because many of the foundational datasets underlying the model are unavailable for those locations. In terms of spatial resolution, dGeo uses U.S. Census tracts that have populations (median = 4,000 people) and geographic areas (median = 5 km²) consistent with the upper limit of existing district-heating systems. dGeo only considers buildings in the residential and commercial sectors; it does not model the industrial sector (including manufacturing,

agriculture, mining, and other subsectors) because of a lack of sufficient data to model this sector at any defensible level of fidelity.

C.3 Heating and Cooling Sector: Direct-Use District-Heating Systems

As discussed in the main body of the *GeoVision* report, analysis of geothermal direct-use applications was limited to district-heating systems (see Section 4.2.1). In addition, due to a lack of consumer behavior data on how communities adopt technologies such as district-heating systems, the analysis is limited to the resource, technical, and economic potential of district-heating systems (step 4 of the dGeo model framework). The information and graphics in this section are sourced primarily from McCabe et al. 2019, Gleason et al. 2017, and Mullane et al. 2016.

C.3.1 Resource Potential

For district heating, dGeo considers resources in the range of 30°C to 150°C and less than 3 km deep, including both hydrothermal and EGS. The resource potential in dGeo is based on a previous study by Mullane et al. 2016 investigating the location, temperature, and amount of stored heat of low-temperature (<150°C) and relatively shallow (<3,000 m) hydrothermal and EGS resources in the United States.

C.3.1.1 Hydrothermal Systems

Hydrothermal systems are classified into four model types, following the convention of Sorey et al. (1983):

1. *Isolated springs and wells*: one or a group of nearby wells or springs producing geothermal fluid; generally have a reservoir volume of less than 1 km³
2. *Delineated-area convection systems*: characterized by an upwelling of geothermal water with subsequent lateral flow into shallow aquifers larger than 1 km³; with or without surface manifestations
3. *Sedimentary basins*: thermal sedimentary aquifers overlain by low thermal-conductivity lithologies; contain trapped thermal fluid and have flow rates sufficient for production without stimulation
4. *Coastal plains sedimentary systems*: similar to sedimentary systems, although typically occur along coastlines and may be underlain by an intrusive igneous body producing heat by radioactive decay; natural flow rates are sufficient for production without stimulation.

Data for all four types of hydrothermal systems came primarily from three USGS studies, including (in descending order of contribution to this analysis): USGS Circular 892 (Reed et al. 1983), USGS Circular 790 (Muffler 1979), and USGS Fact Sheet 2008-3082 (Williams et al. 2008b). These studies were chosen due to their comprehensive, nationwide coverage, as well as their internal consistency in terminology and methods. USGS Circular 892 focuses on resources in the range of 15°C to 90°C, whereas the latter two studies include additional resources in the range of 90°C to 150°C. For most sites, data for most of the parameters (e.g., temperature, depth, thickness, area per production well) were available directly from the original studies or a detailed review of the associated primary sources; however, in several cases, gaps in the data were filled by searching for supplemental, site-specific studies. Data gaps occurred most commonly in location and reservoir area.

Table C-7 shows the estimated resource potential for each of the hydrothermal system models, and Figure C-21 shows their distribution within the United States. The accessible resource is quite large, but the portion that can be extracted given physical and current technological limitations (mean resource) is far less. For comparison, the total low-temperature thermal demand in the United States is roughly 12 exajoules annually.¹¹² The beneficial heat—representing the best estimate of how much heat can realistically be utilized for end uses with existing technology—represents roughly half of the mean resource (note: 11.2 million GWh_{th} = 40.3 exajoules).

¹¹² An exajoule is 10¹⁸ joules. A joule is defined by EIA as, “The meter-kilogram-second unit of work or energy, equal to the work done by a force of one newton when its point of application moves through a distance of one meter in the direction of the force” (EIA Glossary n.d.). One quad is equal to 1.055 exajoules.

Resource Model	Accessible Resource (Exajoules = 10^{18} J)	Mean Resource (Exajoules = 10^{18} J)	Beneficial Heat (GWh _{th})
Isolated Springs and Wells	180	22	2.9 million
Delineated-Area Convection	130	7	0.7 million
Sedimentary Basins	28,000	60	7.5 million
Coastal Plains	80	1	0.1 million
Total	28,390	90	11.2 million

Table C-7. Resource Assessment Estimates for All Four Hydrothermal Model Types

Source: Mullane et al. 2016

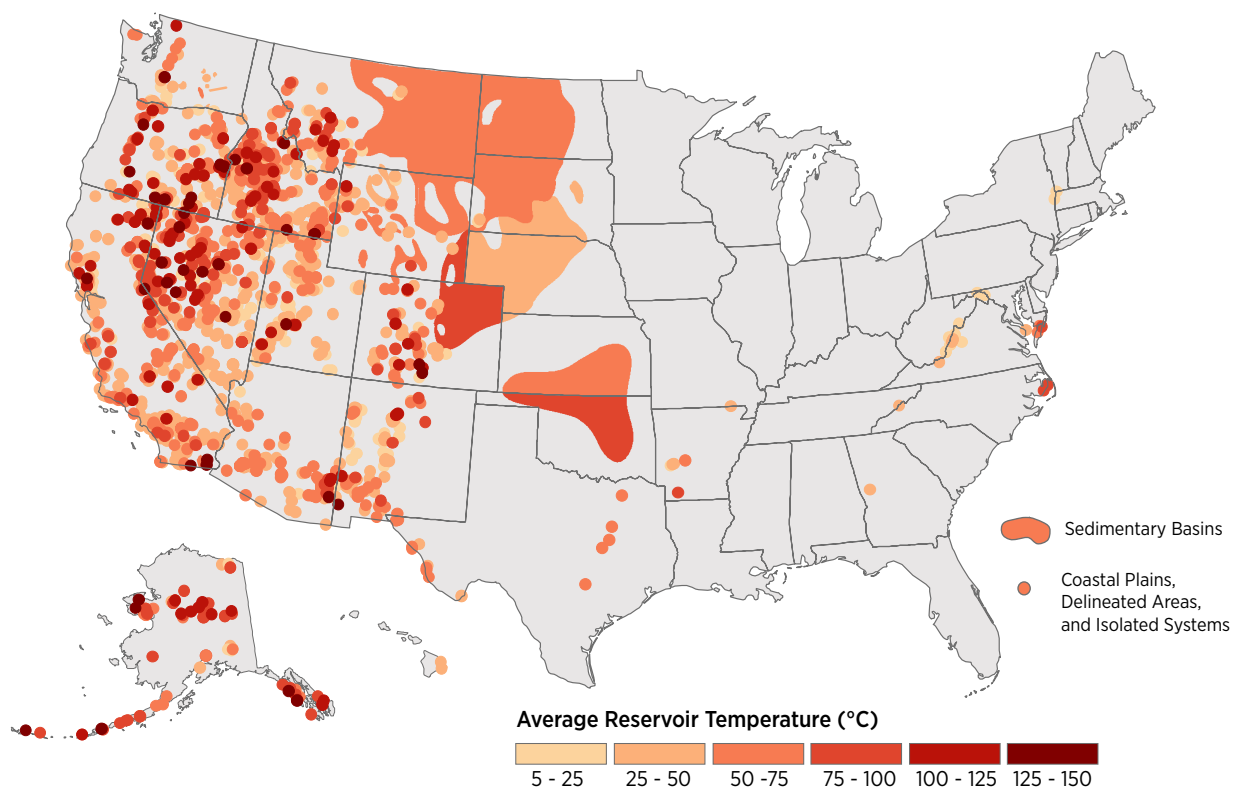


Figure C-21. Map of hydrothermal resources at specified temperatures for the United States

Source: Mullane et al. 2016

C.3.1.2 Enhanced Geothermal Systems

EGS includes two primary subtypes:

1. *EGS sedimentary basins*: differ from “hydrothermal” sedimentary systems in that they lack water and/or permeability.
2. *Shallow (<3 km) low-temperature EGS¹¹³*: low-conductivity basement rock at a depth of 3 km or less; in theory, may be accessed in any location given sufficient depth and reservoir stimulation. Referred to as “shallow EGS” in contrast to “deep EGS,” which is generally hotter and considered for electricity generation.

In comparison to hydrothermal resources, very few studies have focused on shallow-EGS resources. For EGS sedimentary basins, the *GeoVision* analysis resource-potential estimate drew from work by Porro et al. 2012. The Porro et al. study assessed the accessible resource (i.e., heat-in-place) for 15 large sedimentary basins in the United States. Although the authors did not explicitly identify their focus on EGS resources, language in the report indicates that recovery of heat from basins in the study would require “injection and extraction of fluid” and potentially “stimulation and enhanced recovery methods.” Therefore, this study was treated as an EGS resource assessment.

Table C-8 shows the accessible resource base for low-temperature sedimentary EGS for those portions of the 2012 Porro et al. study. The estimates consider only temperatures in the range of 100°C–150°C and to depths of 3 km.

Basin Name	Accessible Resource Base (Exajoules = 10 ¹⁸ J)
Denver	5,700
Great Basin	2,300
Fort Worth	1,100
Raton	280
Total	9,380

Table C-8. Resource Estimates for Low-Temperature Sedimentary Enhanced Geothermal Systems

Source: Mullane et al. 2016

Table Note: Estimates recalculated from Porro et al. 2012.

The geothermal resources available from shallow (≤ 3 km) low-temperature EGS have not been studied in the same detail as either low-temperature hydrothermal systems or deeper EGS systems. SMU has produced reliable, high-quality temperature-at-depth maps for the deep lithosphere (≥ 3 km) (Blackwell et al. 2011), which were used in the development of EGS resource supply curves for the electricity sector (Appendix C.1.1.3 and C.1.1.4). However, equivalent studies have not been performed at shallower depths, due at least in part to uncertainties regarding water intrusion and aquifer effects at such depths. For shallow low-temperature EGS resources, an original analysis was completed to provide a rough estimation of resources available in the shallow subsurface, relying on datasets from SMU (Blackwell et al. 2011, Blackwell et al. 2014) and the Association of American State Geologists Geothermal Data Repository 2012. Specifically, the analysis applied geostatistical interpolation methods to publicly available bottom-hole temperature data from oil, gas, and water wells to infer approximate temperature-at-depth contours for the United States at multiple depth intervals. From these contours, a rough estimate of the shallow (≤ 3 km), low-temperature (30°C–150°C) accessible resource was estimated for a spatial grid covering the continental United States at a resolution of about 4 km \times 4 km.

¹¹³ In the original Mullane et al. 2016 study, these resources are referred to as “low-conductivity, hot dry rock.” The name is changed here to provide consistency with the electric-sector resources and prevent confusion.

Figure C-22 shows the estimates of accessible resource calculated from the temperature estimates, along with upper and lower estimates based on the 95% confidence intervals. In total, the shallow (≤ 3 km), low-temperature (30°C – 150°C) accessible EGS resource in the continental United States is estimated to be about 800 million TWh, with 95% confidence bounds of 500 million–1,100 million TWh. These estimates are roughly consistent with an assessment by Tester et al. 2006, which estimated a total accessible EGS resource for the continental United States in the deep subsurface (3–10 km) of 13 million exajoules, or about 3,600 million TWh. Given that the *GeoVision* analysis focused on shallower depths with correspondingly lower temperatures and a total volume of less than half that studied by Tester et al. 2006, the *GeoVision* analysis estimate is expected to be less than the Tester et al. estimate, but roughly the same order of magnitude.

C.3.2 Technology Costs and Assumptions

C.3.2.1 Geothermal Direct Use Levelized Cost of Heat

The *GeoVision* analysis looks at two scenarios for evaluating the future potential of district-heating systems in the United States. The scenarios use many of the same assumptions as the scenarios of the same names in the electric-sector analysis. The district-heating scenarios generally use the same assumptions as in the electric sector to describe technology cost and performance associated with developing the subsurface geothermal resource. The district-heating scenarios are:

1. The Business-as-Usual (BAU) scenario, which incorporates existing and anticipated future technical, cost, and financial parameter values of district-heating systems, assuming similar market conditions for the next 30 years or more and no investments made to improve technology or financing parameters.

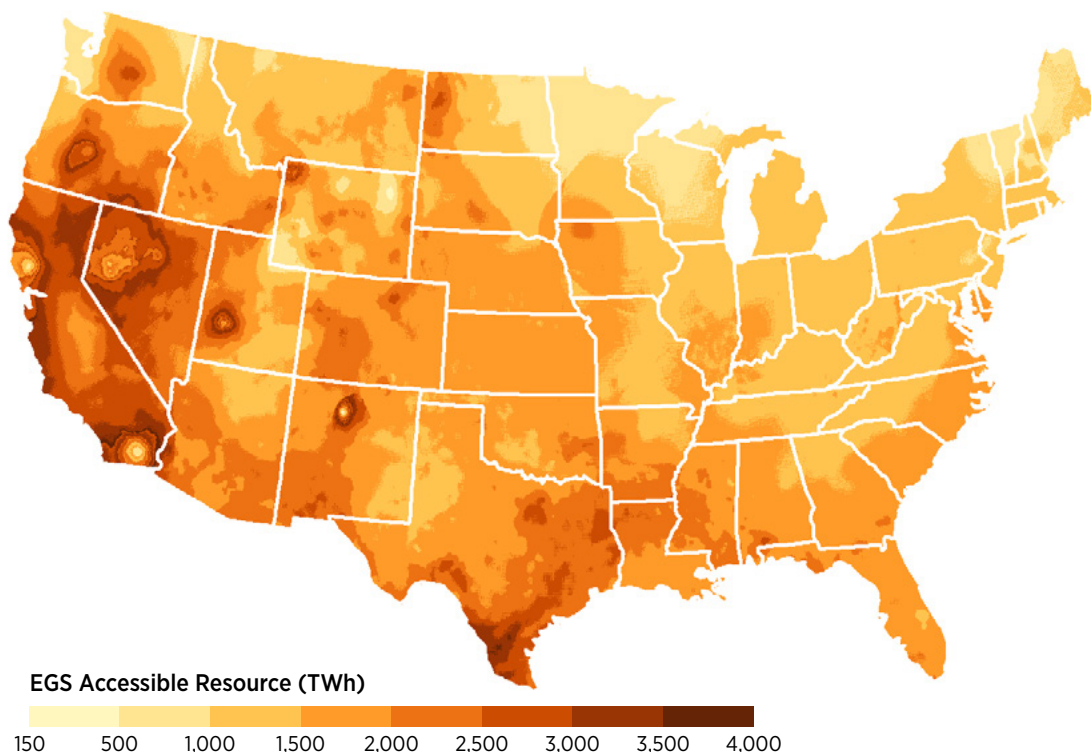


Figure C-22. Map of estimated accessible resource in the shallow subsurface (300–3,000 m)

Figure Note: The estimates presented in Mullane et al. 2016 are meant to provide only preliminary, order-of-magnitude estimates (Mullane et al. 2016).

2. The Technology Improvement (TI) scenario, which assumes improvements to some district-heating parameters, including technical, cost, and financial parameters. The improvements include: 1) a 50% reduction in drilling costs, 2) an increase in EGS well flow rate from 40 liters/second (L/s) to 110 L/s, 3) an approximate 15% decrease in discount rate, and 4) an average 15% decrease in exploration-related costs. These improvements are modeled to occur gradually (linearly) from 2016 to 2030 and stay constant through 2050. The district-heating TI scenario does not include the land-access barrier or construction timeline reductions that the electric-sector TI scenario does.

dGeo performs a set of simulations to derive the levelized cost of heat¹¹⁴ (LCOH) associated with each of the locally available direct-use resources for district heating. These calculations are based primarily on the hydrothermal and EGS resources in each census tract, as well as on the costs associated with developing and supplying each resource to buildings in the tract. LCOH is calculated for each potentially developable well in each tract, considering the following five components:

1. **Subsurface installation costs:** The subsurface costs associated with direct-use district-heating development are primarily a function of exploration, drilling, and—for EGS—reservoir stimulation. Drilling costs in dollars are calculated based on the depth to the resource.
2. **Plant installation costs:** The costs associated with building (or expanding) a plant for each district-heating production well are calculated based on a user input of normalized costs ($\$/kW_{th}$) and the capacity of the production well. Additional costs are associated with the installation of natural-gas peaking boilers, which are used to supplement the direct-use heat utilization at times of peak demand.
3. **Distribution installation costs:** dGeo accounts for the costs of building a distribution network that can transport hot water from a central plant to buildings in the census tract. To do so, the model estimates the total required length of piping for each tract and then normalizes the cost based on the proportion of heat actually supplied by each local resource.
4. **Operating costs:** dGeo considers five main operating costs associated with each district heating plant: 1) fixed O&M for the plant, 2) fixed O&M for the wells, 3) reservoir pumping costs, 4) distribution pumping costs, and 5) natural-gas peaking boiler fuel costs.
5. **System financing:** Plant financing is modeled in dGeo as a function of a series of user-defined parameters, including inflation rate, interest rate, interest rate during construction, rate of return on equity, debt fraction, tax rate, construction period, construction finance factor, plant lifetime, depreciation period, and depreciation schedule.

A 2017 study by Beckers and Young on district-heating cost, performance, and financial parameters provides the basis for the dGeo input data for the LCOH calculation of district-heating systems (Beckers and Young 2017). The Beckers and Young study used a review of more than 40 U.S. and international geothermal studies as well as the studies by the other *GeoVision* task forces to derive BAU and TI scenario values for 31 performance, cost, and financial parameters. Where applicable, the dGeo values use those derived by other *GeoVision* analysis supporting task forces (e.g., exploration and drilling costs) for electricity-sector assessment in the *GeoVision* analysis. Most of the parameters common to both the heat and electricity-sector analyses are subsurface related (e.g., well capital, O&M maintenance costs, EGS well flow rate, exploration costs) and were assessed by the Resource Exploration and Confirmation task force and the Reservoir Maintenance and Development task force (Doughty et al. 2018, Lowry et al. 2017). Other parameters relevant to the *GeoVision* analysis and studied by the other task forces are not directly transferable to geothermal direct use. For example, the discount rate used for calculating the cost of financing is assumed to be less for district-heating systems than power plants because district-heating systems are considered (in dGeo) to be financed with low-interest

¹¹⁴ Levelized cost of heat is the net present value of the unit cost of thermal energy (heat) over the lifetime of a thermal energy source. It is analogous to levelized cost of electricity, but applies to direct-use geothermal resources.

municipal bonds and run by municipalities. Finally, some parameters are unique to district heating and are based on a review of external studies (e.g., the heat distribution network and central plant capital and O&M costs, the district-heating system construction period, typical peaking boiler sizing and efficiencies). Table C-9 provides a summary of key default costs used in the dGeo model for district-heating systems.

C.3.2.2 District-Heating Supply Curves

Using the inputs described previously, dGeo calculates the LCOH for each potential direct-use district-heating production well. The model then combines these values for all potential production wells to construct a supply curve, quantifying the cumulative thermal capacity within the tract associated with increasing values of LCOH. Figure C-23 shows the resulting hydrothermal resource supply curve for the BAU and TI scenarios. The figure shows an average reduction in LCOH in the TI scenario of about 20%.

Cost Type	Input Parameter	Value
Subsurface Costs	Drilling Cost Improvement (% Reduction)	0
	EGS Reservoir Stimulation Costs (\$MM/wellset)	1.25
	Hydrothermal Exploration Drilling Costs (\$MM/wellset)	3.30
	EGS Exploration Drilling Costs (\$MM/wellset)	5.00
	Hydrothermal Exploration Non-Drilling Costs (\$MM/wellset)	0.78
	EGS Exploration Non-Drilling Costs (\$MM/wellset)	3.38
Surface Plant Costs	Plant Installation Costs (\$/kW _{th})	100
	Natural Gas Peaking Boiler Costs (\$/kW _{th})	50
	O&M Labor Costs (\$/kW _{th} /year)	25
	Plant O&M Costs (% of plant capital costs/year)	1.0
	Wellfield O&M Costs (% of well capital costs/year)	1.5
Residential and Commercial End-User Costs*	System Interconnection Costs (\$)	2,000
	New or Compatible System Installation Costs (\$/ft ²)	1.5 / 1.7
	Incompatible System Installation Costs (\$/ft ²)	2.0 / 2.3
	Fixed O&M Costs (\$/ft ²)	0.015 / 0.017

Table C-9. Default Cost Parameter Values used in dGeo for District-Heating Systems

Source: Gleason et al. 2017

Table Notes: *Residential and commercial end-user cost values for New or Compatible System Installation Costs, Incompatible System Installation Costs, and Fixed O&M Costs are reported as residential/commercial (e.g., New or Compatible System Installation Costs for residential systems are 1.5 \$/ft², and New or Compatible System Installation Costs for commercial systems are 1.7 \$/ft²).

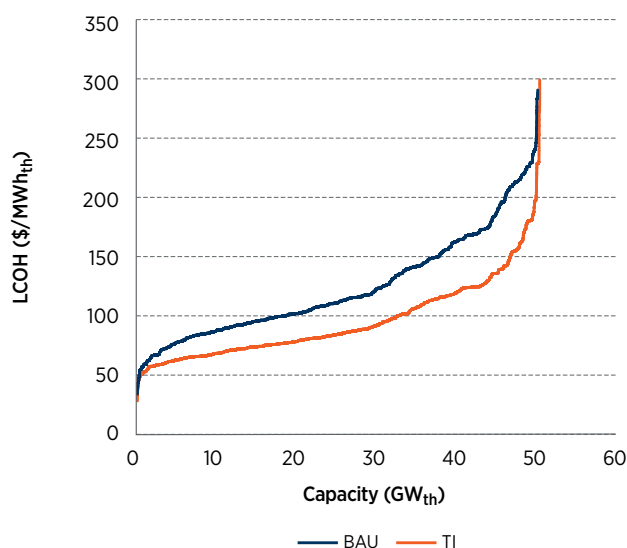


Figure C-23. Geothermal district-heating supply curves for the Business-as-Usual and Technology Improvement *GeoVision* analysis scenarios

Source: McCabe et al. 2019

Figure Note: This figure includes only hydrothermal resources as an example.

C.3.2.3 Demand-Side Levelized Cost of Heat

A 2016 study by McCabe et al. on low-temperature thermal demand in the United States provides the dGeo input data for regional demand for space and water heating in the residential and commercial sector (McCabe et al. 2016). Regional cost of fuel comes from the EIA *Annual Energy Outlook* projections (EIA 2016d). The costs of alternative space-heating systems (e.g., natural-gas furnace) were based on data developed in Liu 2010 and Liu et al. 2016. Fuel costs and alternative-system costs were used in dGeo to estimate heating bill savings.

The model estimates demand using the mutated agents at each time step. From the agent attributes, dGeo calculates the price each agent would be willing to pay for heat provided by a district-heating system. This price is derived as the agent's LCOH, which accounts for the following three components:

1. Interconnection and Equipment Costs: The costs of joining a district-heating system include a one-time fixed interconnection fee and the costs of purchasing and installing the required space-heating and

hot-water system to actually use the district heat supplied to the building. The latter is calculated for each agent based on the normalized equipment costs and the agent's building size.

2. Fixed O&M Costs: These costs consist of fixed costs of servicing and maintaining the space-heating and hot-water equipment within each building. They are derived from the agents' attributes for direct-use end-user O&M costs (district heating in this instance) and building size.

3. Annual Costs of Heat and Hot Water: dGeo calculates the annual costs of heat using each agent's incumbent space-heating and hot-water fuel types, site energy consumption of space heat and hot water, and costs of energy.

Table C-9 includes the values for interconnection, equipment, and fixed O&M costs. Each of these components is calculated in levelized terms by simply amortizing the costs over the expected lifetime of a district-heating system; no financial terms are included, nor are cash flows derived. dGeo calculates the LCOH by subtracting the interconnection, equipment, and fixed O&M costs from the annual costs of heat and hot water and dividing the result by the site energy consumption for space and water heating by the agent (in MWh). dGeo assumes the calculated agent LCOH is the price the agent would be willing to pay to connect to a geothermal direct-use district-heating system.

C.3.3 Economic Potential

dGeo's estimation of the economic potential for geothermal direct-use district heating is calculated by simulating the local supply and demand for district heating for each census tract and then determining the portion of supply with sufficiently low price to meet the demand. This process requires calculating LCOH for both supply and demand. dGeo combines the supply and demand curves to determine the economic potential within each tract; to do so, the model intersects the supply and demand curves to identify the settling price and quantity. The cumulative capacity associated with this intersection defines the economically viable district-heating capacity within the tract, and, therefore, its economic potential.

Meanwhile, the LCOH associated with the intersection of the demand and supply curves defines the price at which thermal energy delivered by geothermal district heating could be purchased and sold within the tract. An example is shown in Figure C-24. The sum of all economically viable geothermal direct-use capacity across all tracts determines the economic potential for district heating at each model time step.

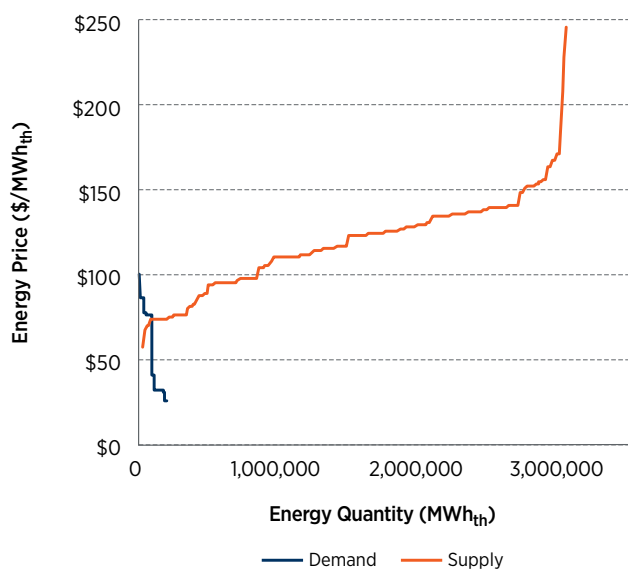


Figure C-24. Example of the overlay of demand and supply curves for a single census tract, where the point of intersection represents the settling price and quantity for heat

Source: Gleason et al. 2017

C.4 Heating and Cooling Sector: Geothermal Heat Pumps

dGeo analyzes GHP systems as individual, site-level resources for each agent. GHP systems can use several different ground heat exchanger configurations (e.g., closed-loop horizontal and vertical, standing-column wells, open- and closed-loop pond). However, dGeo only models the most common and widely applicable of these configurations: closed-loop horizontal (i.e.,

field loops) and vertical (i.e., borehole) systems. The information and graphics in this section are sourced primarily from Liu et al. 2019 and Gleason et al. 2017.

C.4.1 Technology Costs and Assumptions

The dGeo model includes seven categories of inputs for GHPs: GHP costs, GHP performance, HVAC costs, HVAC performance, GHP siting, financing, and Bass diffusion.¹¹⁵ The assumptions and calculations for these inputs are summarized in sections C.4.1.1–C.4.1.5.

C.4.1.1 Geothermal Heat-Pump Cost and Performance

GHP system costs comprise the following components: heat pump, “rest-of-system” costs for the indoor energy delivery system (e.g., ductwork, piping), fixed annual O&M, and the ground heat exchanger. Rest-of-system costs are only applied to new construction. Cost values are derived from user-input parameters provided by year, sector and—in the case of ground heat exchanger costs—by system configuration (i.e., vertical and horizontal). Input parameters are provided in size-normalized values (e.g., \$/cooling ton, \$/ft², \$/ft) and multiplied by the relevant agent attributes (e.g., required cooling capacity, building area, required ground heat exchanger length) to calculate actual GHP costs for each agent.

The modeled GHP systems are those typically used in the United States—central forced-air systems with two-stage GHP units for residential applications; and distributed systems with multiple single-stage GHP units for commercial applications. The typical nominal cooling efficiency of the two-stage GHP unit is 18.2 energy efficiency ratio (EER)¹¹⁶ at full capacity and 27 EER at 76% of full capacity. The typical nominal heating efficiency of the two-stage GHP unit is 4 coefficient of performance (COP) at full capacity and 4.5 COP at 76% of full capacity. The typical nominal efficiencies of the state-of-the-art single-stage GHP units are 20 EER and 4.2 COP. The ground heat exchanger is sized

¹¹⁵ The Bass diffusion is the “diffusion of innovations” framework (Bass 1969, Rogers 2003). Under this framework, cumulative diffusion of a novel technology into a market is assumed to follow a logistic “S”-shaped trajectory.

¹¹⁶ The EER is the cooling capacity (in British thermal units [BTU]/hour) of the unit divided by its electrical input (in watts) at standard conditions.

to maintain the fluid temperature from the ground loop (the entering fluid temperature to the GHP unit) within the range of (-1)°C–35°C for given building load and ground thermal properties. The modeled ground heat exchangers could be vertical or horizontal closed-loop, depending on land availability and associated installation cost.

The cost of GHP equipment includes the capital costs for GHP equipment and the associated installation cost, including material, labor, overhead, and profit. The modeled commercial GHP systems use multiple small GHP equipment (usually with capacities less than 5 cooling tons) in a distributed configuration; residential GHP systems also usually have less than a 5-cooling-ton capacity. dGeo calculates the cost of GHP equipment using a correlation between the size of a GHP equipment item and its normalized cost (\$/ton), which is derived from available RSMMeans 2016 cost data for 1-, 2-, and 5-cooling-ton GHP equipment (Figure C-25). For commercial GHP systems, it is assumed that the average capacities of the GHP equipment is 5 cooling tons. The normalized GHP cost is multiplied by the normalized capacity of a GHP system in a given climate zone (expressed as tons/ft²) and the floor space of the reference building to determine the total GHP equipment cost.

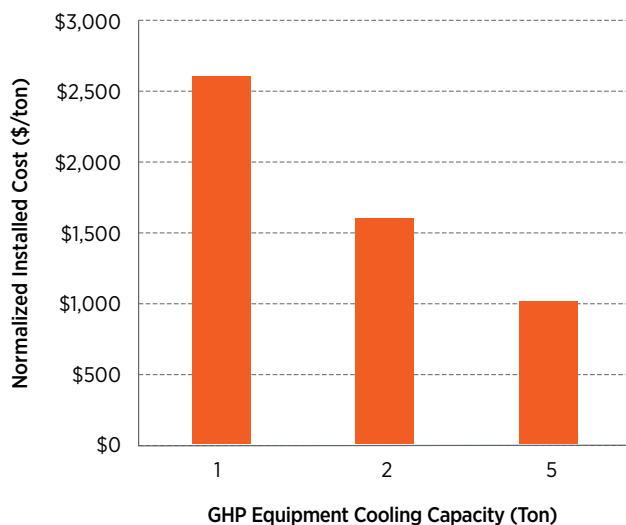


Figure C-25. Installed costs of 1-, 2-, and 5-cooling-ton GHP equipment

Source: RSMMeans 2016

The rest-of-system cost (indoor energy-delivery system) includes the installed costs of all components except for the ground heat exchanger and the GHP equipment. Rest-of-system components include ductwork, hydronic piping, circulation pumps, and necessary system-level controls. The analysis assumed a normalized cost for multizone ductwork of \$2,802/ton (RSMMeans 2016) and \$1.70/ft² for the hydronic piping system including circulation pumps (GBC 2016). The central air ductwork that is most commonly used in residential buildings can be used for both the GHP and conventional HVAC systems. Therefore, there is no difference in the rest-of-system cost for a GHP system and a baseline HVAC system for new constructions or retrofits. For commercial buildings, if the baseline HVAC system uses multizone ductwork, a new hydronic piping system including circulation pumps is needed to implement a distributed GHP system.

The assumptions also account for the O&M cost, which is the annual total cost for operating and maintaining a GHP system. The O&M cost is assumed to scale with the size of the system, which is represented by the total floor space served by a GHP system and expressed as \$/ft²/year. Based on a prior survey by Cane and Garnet, the log-mean of the surveyed total annual maintenance costs of various commercial GHP systems in 1996 was \$0.061/ft² (base), \$0.074/ft² (in-house), and \$0.084/ft² (contractor)(Cane and Garnet 2000). The average of these three costs was adjusted with 3% inflation rate to get the 2016-dollar value of \$0.13/ft², which is used as the commercial GHP O&M cost input to dGeo. The O&M cost for residential GHP systems and HVAC systems is negligible. This does not include the energy cost for running these systems, which is calculated separately based on annual energy consumption of the GHP system and the energy price at a given year.

The cost of the ground heat exchanger includes all the costs and markups for drilling bores (or trenching), inserting heat-exchanger loops, grouting the bores (or backfilling the trenches), and looping to the heat pump. It contributes the most to the overall cost of a GHP project. The cost of a ground heat exchanger is calculated based on the average normalized cost of ground heat exchanger at a location and the size of the ground heat exchanger required to provide needed capacity with given ground thermal properties. dGeo assumes a single normalized vertical closed-loop

ground heat exchanger cost of \$14/ft, equal to the nationwide median value for all geologies (Battocletti and Glassley 2013). It is assumed that the installed cost of vertical closed-loop ground heat exchangers for residential and commercial installations are equal. The installed costs of horizontal closed-loop ground heat exchangers are obtained from a major GHP manufacturer in the United States (Brown 2017). A nationwide average value of \$1,850/cooling ton is used.

Ground thermal properties, including undisturbed ground temperature and effective ground-thermal conductivity, are critical parameters for sizing ground heat exchangers. Whereas the undisturbed ground temperature at a location can be estimated based on local historical weather data or using the national map of undisturbed ground temperature, the effective ground-thermal conductivity values, which accounts for different soils and rocks along the depth of a borehole and underground water movement, are affected by many factors, including moisture content, soil texture, organic content, mineralogy, and compaction in the soil, as well as the geology of the underlying bedrock. dGeo uses regional distributions of ground-thermal conductivity based on thermal conductivity values from rock samples from 68,251 oil and gas wells (SMU 2016) to populate agents with ground-thermal conductivity ranges. The model draws from census-division-level estimates of the 25th, 50th, and 75th percentiles of ground-thermal conductivity values and assigns each agent with a randomly assigned GTC value. This approach does not account for local spatial autocorrelation in ground-thermal conductivity, which is highly probable in most locations because of local or intraregional geologic conditions. As a result, dGeo economic calculations may not reflect important local variations in ground heat exchanger length, and the resolution of ground-thermal conductivity data is a component of the model that could be improved in future work.

C.4.1.2 Siting Constraints

Siting constraints of GHP systems are affected by separate inputs for vertical and horizontal ground heat exchanger configurations. For vertical systems, users must provide two parameters:

- Area per Borehole (ft²/borehole): This input is a proxy for well spacing, and it controls the amount of land area required for each vertical borehole. dGeo assumes an area per borehole of 400 ft².
- Maximum Well Depth (ft): This input controls the maximum depth of each borehole. dGeo assumes a maximum well depth of 400 feet.

For horizontal systems, users provide the following two inputs:

- Trench Spacing (ft): This input specifies the distance between trenches within which horizontal loops are installed. dGeo assumes a trench spacing of 15 feet.
- Trench Length per Cooling Ton (ft/cooling ton): This parameter specifies the length of trenching required by the horizontal configuration to provide a cooling ton of capacity. All of these parameters are single inputs that do not vary over time, sector, or any other factor. dGeo assumes 150 ft/cooling ton.

C.4.1.3 Heating, Ventilation, and Air-Conditioning System Cost and Performance

As dGeo iterates over time steps, it attributes each agent with costs for prospective new conventional HVAC equipment. These costs capture the following components: HVAC equipment (e.g., furnace, air conditioner), rest-of-system costs (e.g., ductwork, piping), and fixed annual O&M. dGeo calculates these costs from user-input parameters specified by year and sector. The inputs are provided in normalized units (e.g., \$/cooling ton and \$/ft²); dGeo multiplies these parameters by each agent's corresponding size attributes to calculate actual costs.

For residential buildings, three conventional HVAC systems are considered based on EIA's Residential Energy Consumption Survey (EIA 2013, EIA 2016b): 1) packaged air conditioner with gas/oil/propane-fired furnace, 2) packaged air conditioner with electric resistance, and 3) air-source heat pump with electric resistance. RSMMeans 2016 cost data for the heating and cooling equipment of the three systems are used to derive two correlations between the heating or cooling capacity and the installed costs (Figure C-26 and Figure C-27).



Figure C-26. Installed costs of typical residential space-cooling equipment

Source: RSMMeans 2016

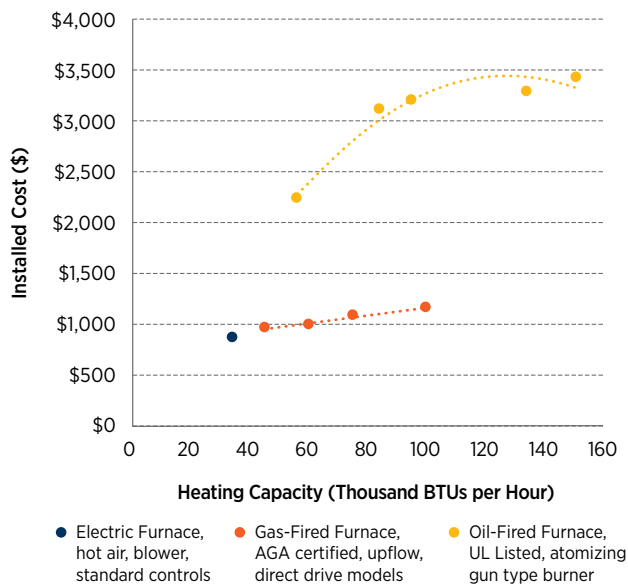


Figure C-27. Installed costs of typical residential space-heating equipment

Source: RSMMeans 2016

For commercial buildings, it is assumed that the conventional HVAC system is a packaged variable air volume (VAV) system with standard features, including multizone control, electric cool, gas heat, and air-side economizer. RSMMeans 2016 cost data for packaged

VAV equipment (the outdoor HVAC equipment only, without ductwork inside the building) with cooling capacities ranging from 15–105 tons were used to derive a correlation between cooling capacity and the installed cost of the packaged VAV equipment (Figure C-28). The cost of the furnace pack used in the packaged VAV equipment is not very sensitive to its capacity, so the installed cost of packaged VAV equipment was based solely on its cooling capacity. It is assumed that multiple packaged VAV equipment (each with a capacity not larger than 105 tons) is used for systems with larger than 105-ton cooling capacity. For systems with less than 15-ton cooling capacity, cost was estimated by proportionally decreasing the cost of the 15-ton packaged VAV equipment.

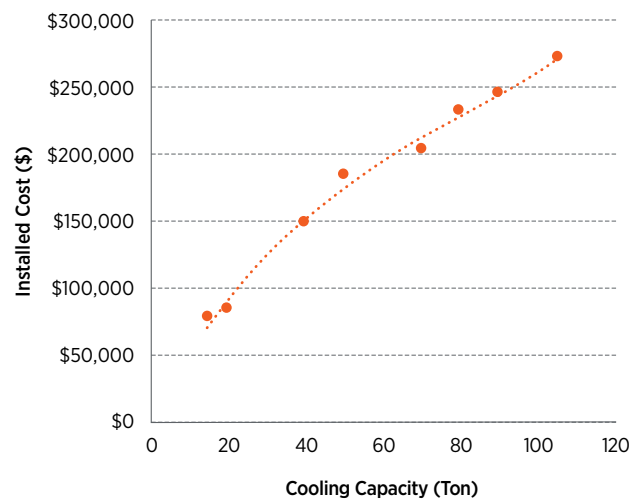


Figure C-28. Installed costs of typical packaged variable-air-volume equipment

Source: RSMMeans 2016

As noted previously, the central-air ductwork that is most commonly used in residential buildings can be used for both GHP and conventional HVAC systems. Therefore, there is no difference in the rest-of-system cost for a GHP system and a baseline HVAC system for both new constructions and retrofits.

As with GHP systems, the O&M cost for residential baseline HVAC systems is negligible. The O&M cost for commercial baseline HVAC system is adopted from the result of a 1999 American Society of Heating, Refrigerating and Air-Conditioning Engineers study. The mean annual maintenance cost of packaged VAV systems is estimated as \$0.64/ft²/year (in 2016 dollars, assuming a 3% inflation rate).

C.4.1.4 Fuel and Electricity Costs

Within the dGeo model framework, agents evaluate current and anticipated future expenditures associated with the energy consumed for operating the potential GHP system as well as the baseline HVAC system for space heating and space cooling. These energy costs are based on the agents' attributes for existing and future energy prices and the site energy consumptions of the GHP and the baseline HVAC system. Energy prices from the AEO 2016 (EIA 2016b) are used in dGeo to represent the price paid to operate the two systems. Figure C-29 shows projected energy prices for the four main fuels modeled in dGeo: electricity, fuel oil, propane, and natural gas. dGeo uses region-specific fuel prices for residential and commercial use.

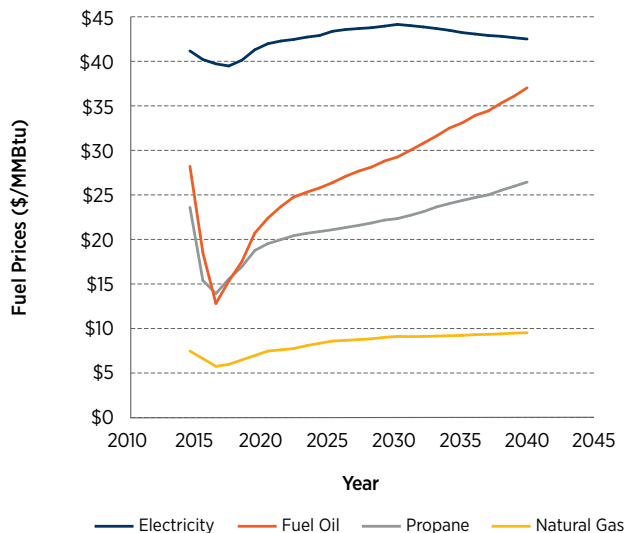


Figure C-29. Projected residential energy prices

Source: AEO 2016 Reference Scenario (EIA 2016)

C.4.1.5 Financing Assumptions

dGeo assumes that heating and cooling system installations are financed through loans. dGeo makes the following capital and financing assumptions when determining the cost and payback of heating and cooling systems:

- Every agent in the model has access to the capital required for a GHP system
- Every agent has access to the same loan terms
- Inflation: 2.5%/year in all cases
- Loan term: 15 years
- Loan rate/interest rate: 6%
- Down-payment fraction: 20% of the total loan amount
- Discount rate: 7%. This parameter is used to control the discount rate used by model agents in their financial calculations.
- Tax rate: 33%.

C.4.2 Geothermal Heat-Pump GeoVision Analysis Scenarios

The *GeoVision* analysis examined two scenarios for evaluating the future potential of GHPs in the United States: a Business-as-Usual (BAU) scenario and a Breakthrough (BT) scenario.

In the BAU scenario, it is assumed that there is no substantial investment in GHP-related research and development and no financial incentives or tax credits for GHPs; as such, technology advancement is slow. The scenario also assumes there will not be any cost reduction in ground heat exchangers and only a moderate increase in the operational efficiency of GHP systems through 2050. For the baseline (conventional) HVAC systems, the scenario assumes there will not be any significant change in the cost and performance during the same period. Therefore, there is only moderate change in the efficiency difference between GHPs and conventional HVAC systems: a 17% increase by 2050. It is assumed that the incremental cost

increase for improving energy efficiency is offset by improvement in manufacturing efficiency and increased economies of scale. Hence, there is no change in the costs or service life of GHPs and baseline HVAC systems.

In the BT scenario, it is assumed that 1) the installed cost of ground heat exchangers is reduced by up to 30% by 2050 because of technical breakthroughs and increased economies of scale resulting from innovative business models; and 2) the operational efficiency of GHP systems is increased up to 50% from 2014 levels by 2030, with no further improvement through 2050. The projected cost reduction for ground heat exchangers is based on an analysis of ongoing global research and development to reduce these costs (Liu et al. 2019). For residential GHPs, the 50% efficiency improvement is from applying advanced GHP equipment (e.g., the ground-source integrated heat pump, which uses a variable-speed compressor, pump, and fan and can provide 100% hot water and space cooling simultaneously). For commercial GHP systems, the modeled GHP equipment is single-stage; if two-stage GHP equipment is used, the annual electricity consumption of GHP systems can be reduced by about 20%. In addition, smart pumping control can cut system power consumption by another 10%. The combination of these two effects will reduce system power consumption by 30%, which is equivalent to increasing the GHP equipment efficiency by 50%.

C.4.3 Resource and Technical Potential

The concept of resource potential has little meaning or value in the context of GHPs, because 1) the nation's GHP resource is extensive enough to support any level of GHP deployment and 2) GHPs can be installed practically anywhere. Instead, the analytical focus was on the technical potential of GHP systems. For dGeo, technical potential is the developable capacity of GHP available and was based on the amount of land available for a geothermal ground loop, technical system performance, and proximity to a suitable thermal end use. Although this definition of technical potential requires that the resource be close to a suitable end use, it is not a demand-constrained

measure; in other words, the technical potential in a given location may actually exceed the amount of energy that would be used by end users in that location. This distinction is consistent with common definitions of technical potential for utility-scale power production technologies, which are typically not constrained by available electric demand.

The technical potential for GHP was calculated using dGeo from the attributes of all building types in the model at each time step. For each region, dGeo determines the maximum cooling capacity that can be installed for each model building type, or agent, for both a vertical and horizontal ground heat exchangers. dGeo multiplies the larger of the two maxima by the number of model agents for each type of model agent in the region. The model repeats this, summing across all agents in a region and then all regions in the model. This methodology amounts to summing the maximum installable capacity of ground heat exchangers across all agents in a region, and it provides an upper bound on the amount of heating and cooling capacity that could be installed in subsequent economic and market potential calculations. Under this formulation, the primary factors that drive the technical potential for GHP are the ground-thermal conductivity, user-input ground heat exchanger area requirements, and parcel sizes of the model agents. Results indicate that more than 580,000 GW_{th} of GHP resource technical potential are available nationwide.

C.4.4 Economic Potential

The economic potential of a renewable resource is defined broadly as the portion of technical potential that is “economically viable” (Brown et al. 2015). dGeo defines the economic potential for GHP as the installable capacity of systems with a positive return on investment, determined based on a positive net present value over a 30-year time frame.

During each model time step, dGeo calculates a new estimate of economic potential for GHPs based on the current state of the model agents. These estimates leverage several agent attributes updated or inherited during the agent mutation process, such as age of space heating and space cooling systems, energy costs specific to these system types, and other user-defined

inputs related to cost and performance of the systems. To derive this estimate, dGeo performs a series of calculations that determine the cashflows associated with installation and operation of a GHP system for each agent. These calculations are detailed in Gleason et al. 2017; in summary, they account for six primary components:

1. **System Payment:** The annual costs of servicing loans (principal repayment and interest) are based on the amount borrowed, loan term, and annual percentage rate. Costs associated with future replacement of the heat-pump component of the GHP system are amortized over the expected heat-pump lifetime, which is assumed to be 20 years.
2. **Fixed O&M Costs:** These costs consist of fixed costs of servicing and maintaining the system over the analysis period and are calculated based on agent attributes for GHP O&M costs and building size.
3. **Annual Energy Costs:** Agents evaluate current and anticipated future expenditures associated with the energy to operate their GHP system for heating and cooling. These costs are based on each agent's attributes for current and future costs of energy and GHP site space-conditioning energy consumption.
4. **Revenue from Incentives:** Agents can receive revenue from incentives such as the investment tax credit, if applicable.
5. **Revenue from Depreciation:** Commercial-sector agents may deduct asset depreciation over the lifetime of the GHP system. This depreciation decreases the tax burden of each applicable agent.
6. **Revenue from Interest Deductions:** All agents may deduct system interest paid from their taxable burden. These deductions provide a source of revenue at the specified taxable rate of each agent. The model assumes that the agent has a sufficient taxable burden to monetize interest deductions fully.

Using these six components, dGeo calculates the cashflows of a GHP installation for each market-eligible

agent, assuming an analysis period of 30 years. To account for the value of a GHP installation relative to continued use of a conventional HVAC system, dGeo also calculates the cashflows associated with the conventional HVAC system of each agent. The cashflow calculations incorporate all of the components used in the GHP calculations, except for revenue from incentives, which the model assumes do not apply to conventional HVAC systems. Furthermore, dGeo assumes that the system payments for a new HVAC system will not begin until some future year, as determined by each agent's expected years to equipment replacement. Subsequent system replacements are amortized over the expected lifetime of a new HVAC system.

To calculate the net cashflows of a GHP system relative to a conventional HVAC system, dGeo subtracts the HVAC cashflows from the GHP cashflows. The resulting net cashflows are then evaluated to determine a series of financial metrics, including payback period, percent monthly bill savings, and net present value. Payback period is determined as the first year with a net-positive cumulative cashflow, while percent monthly bill savings are calculated as the mean annual cashflow divided by the mean annual energy costs associated with the conventional HVAC system.

Using the derived net present values for all market-eligible agents, dGeo is able to determine the overall economic potential for GHP. To do so, it identifies all agents with a positive net present value (under either of the available business models), calculates the product of the GHP capacity and the number of buildings associated with each agent, and sums across all agents to determine the total installable capacity with a positive return on investment.

C.4.5 Market Potential

Whereas economic potential considers the portion of renewable resource that is economically viable, market potential considers the portion that is likely to be deployed, given the reaction of consumers in the market to economic factors. dGeo determines the maximum market share for each agent, which is defined as the portion of the potential market that would eventually

adopt the technology given its level of economic attractiveness. dGeo’s methodology for calculating market potential is relatively straightforward. Using the output financial metrics from the economic potential calculations, including payback period and percent monthly bill savings, dGeo determines the maximum market share associated with each agent. Following the conventions of Sigrin et al. 2016 to quantify the maximum market share, dGeo relies on a series of empirically derived market-adoption curves that relate the economic attractiveness of technology adoption and maximum market share. dGeo’s residential agents evaluate host-owned systems based on the payback period. Commercial agents evaluate systems similarly; however, they have the option of using time-to-doubling in addition to the payback period as metrics for evaluating the system. Section 3.2.2.3 and Figure 3-3 in the main *GeoVision* report present these empirically derived market-adoption curves in detail.

C.4.6 Geothermal Heat-Pump Deployment

The final component of the dGeo modeling framework is the simulation GHP technology deployment into the market. dGeo simulates deployment using the “diffusion of innovations” framework, also known as Bass diffusion (Bass 1969, Rogers 2003). Under this framework, cumulative diffusion of a novel technology into a market is assumed to follow a logistic “S”-shaped trajectory (Figure C-30). Technology deployment initially follows slow growth, accelerates as mass-market uptake begins, and then decelerates as the market for the technology reaches saturation. In short, Bass diffusion defines the pattern by which technologies are adopted by a market over time, and it is used by dGeo to influence the rate of GHP adoption given current and past conditions.

For GHP, dGeo models technology deployment following the methodology described in section 5.2 of Sigrin et al. 2016. In brief, dGeo initializes each agent in the model to reflect the historical state-level deployment of GHP (derived from Schoonover and

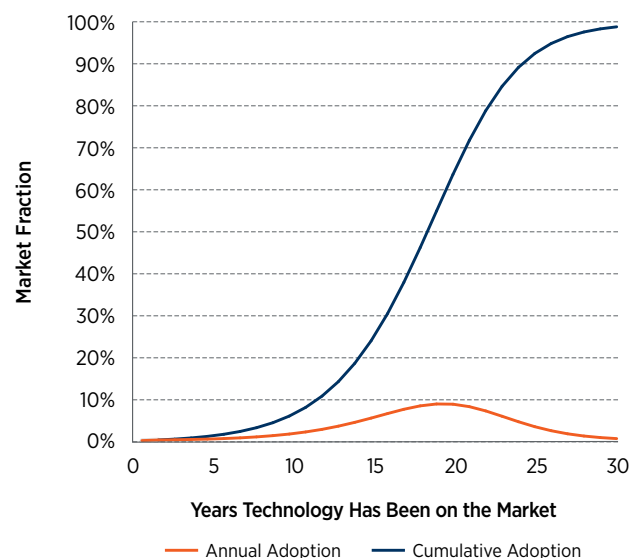


Figure C-30. Annual and cumulative adoption rates simulated using the diffusion-of-innovations framework (for illustrative purposes only)

Source: Gleason et al. 2017

Lawrence 2013). At each model time step, the model determines the amount of new incremental technology adoption as a function of the existing deployment, current market potential (i.e., maximum market share), and location on the Bass diffusion trajectory. These calculations are applied independently to the sub-population of buildings represented by each agent; in aggregate, the population-level deployment across all agent sub-populations exhibits the characteristic Bass diffusion trajectory.

C.4.7 Additional Model Results

The main part of the *GeoVision* analysis report includes results on the economic potential of GHPs for the BAU and BT scenarios, as well as a summary of nationwide GHP economic potential, market potential, and installed capacity as a function of time. The following additional model results put these results in context of heating and cooling sector market share and geographic distribution of deployment.

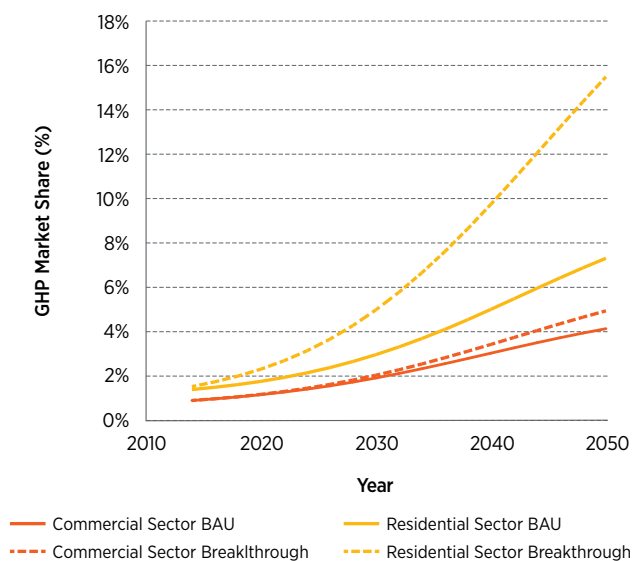


Figure C-31. Projected market share of geothermal heat pumps in commercial and residential sectors from 2014 through 2050

Source: Liu et al. 2019

Figure C-31 illustrates that 4%–5% of commercial buildings are projected to be conditioned by GHPs by 2050. For the residential sector, with the AEO Reference case energy prices, GHPs can realize about 7% market share in the BAU scenario with conservative customer adoption. Residential market share could increase to more than 15% in the BT scenario and more optimistic customer adoption.

Figure C-32 shows the geographical distribution of the normalized installed GHP capacities in 2050. Under BAU (Figure C-32, top), most counties with high installed capacity (more than 20 kW_{th} installed GHP capacity per square km) are in the Northeast, especially New England. The large heating demands and high heating-fuel costs make GHPs more cost effective for space heating in this region. Under the BT (Figure C-32, bottom) scenario, most counties in the Northeast and South Atlantic have high installed GHP capacity.

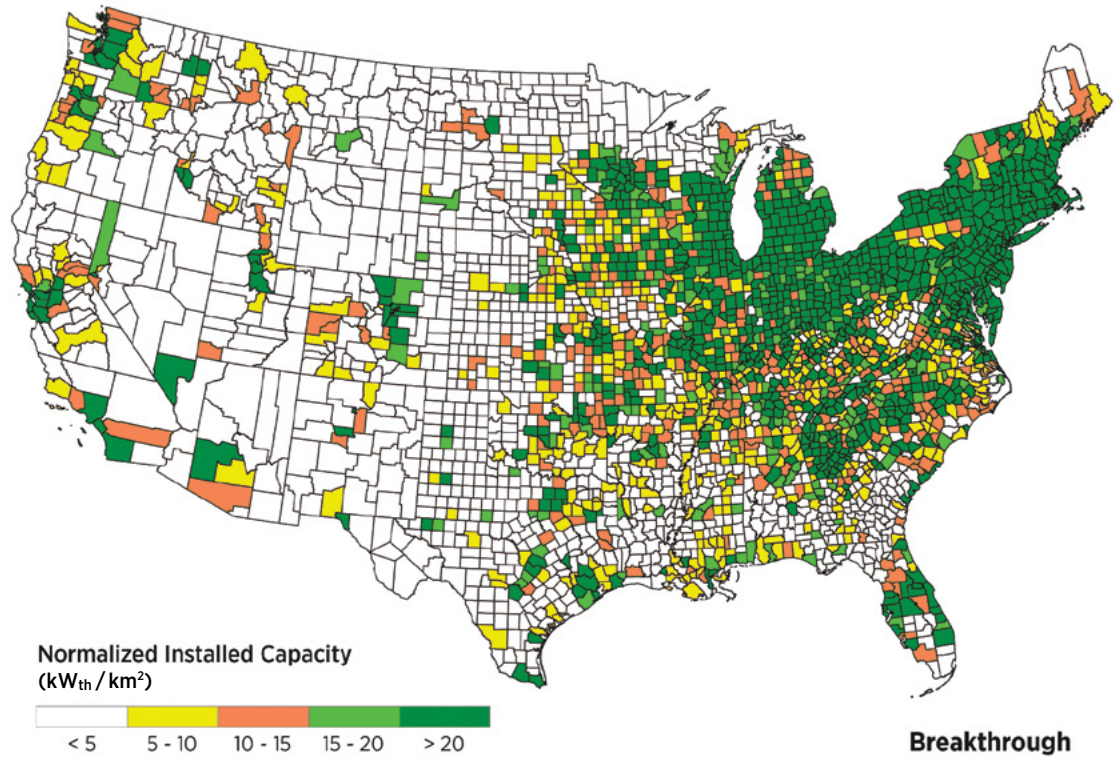
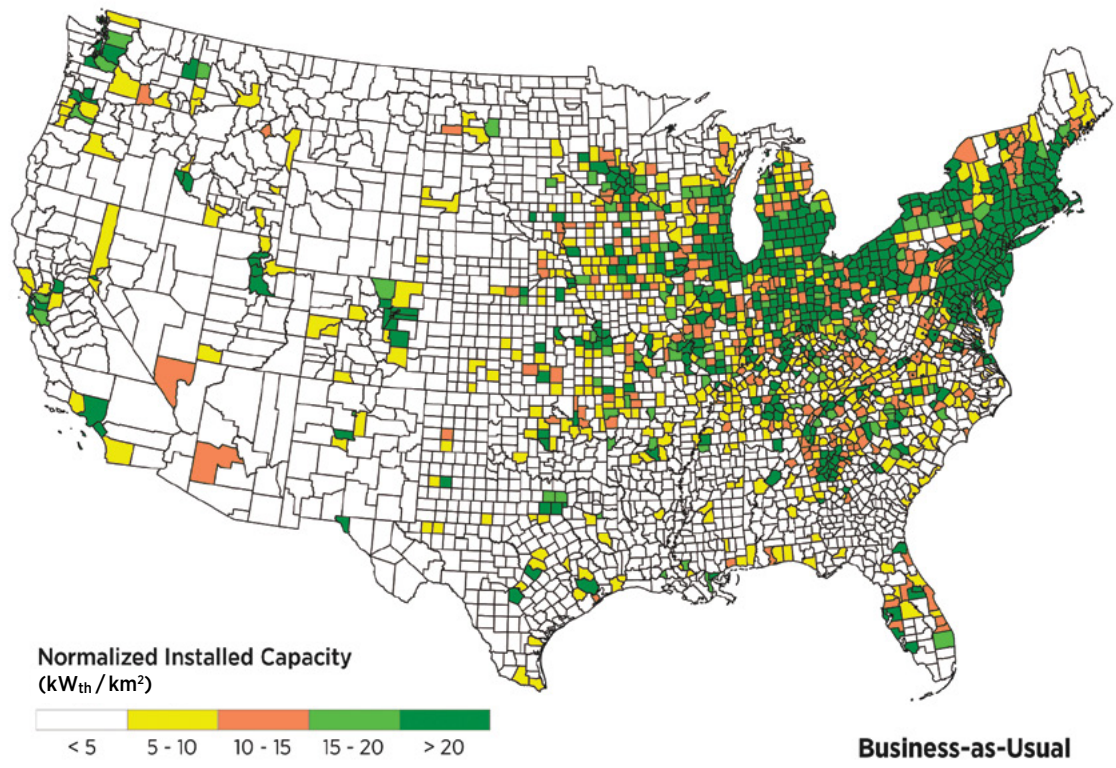


Figure C-32. Installed geothermal heat-pump capacities in 2050: under the Business-as-Usual (top) and Breakthrough (bottom) scenarios
Source: Liu et al. 2019

Appendix D: Contributors

The U.S. Department of Energy (DOE) acknowledges the authors, reviewers, and various contributors listed in this appendix, all of whom contributed to this project since its inception in early 2015. More than 115 individuals representing more than 65 organizations provided technical knowledge, draft text, or review comments.

The DOE Geothermal Technologies Office (GTO) managed the overall *GeoVision* analysis process, ensuring participation of individuals representing a broad range of geothermal stakeholder sectors including, but not limited to, trade organizations, equipment manufacturers, project developers, independent power producers, technical consultants, non-governmental and environmental organizations, electric utilities, state organizations, national laboratories, and federal agencies.

The *GeoVision* analysis relied on the collection, modeling, and analysis of robust datasets through DOE national laboratory partners. Expert input was provided through active participation in seven technical task forces (Section D.3) that focused on:

1. Electricity Potential to Penetration
2. Environmental and Social Impacts
3. Hybrid Systems
4. Institutional and Market Barriers
5. Reservoir Maintenance and Development
6. Resource Exploration and Confirmation
7. Thermal Applications

The technical task forces comprised national laboratory partners coupled with GTO task management and were responsible for producing the foundational work products and basis for the *GeoVision* analysis (see ***GeoVision Analysis Supporting Task Force Reports*** in the References). GTO provided a governance and leadership role in integrating the technical task force work products, guiding the formation of the *GeoVision* analysis objectives, and leading the external and interagency review process. The work of the task forces was also iteratively and transparently reviewed through a group of 20 senior peer reviewers (“Visionaries”).

Following preparation of the draft report and findings, additional review was provided by an external review group of 34 experts who had not previously been involved in preparation of the analysis, findings, or the report. Contributions and support from reviewers were incorporated throughout the development of this report. Collectively, participants in the *GeoVision* analysis process were instrumental in documenting the state of the industry and identifying future opportunities for growth, as well as pinpointing challenges that need to be addressed for the geothermal industry to continue to evolve and contribute value to the nation.

Various offices within DOE provided counsel and review throughout the effort. The DOE’s Office of Energy Efficiency and Renewable Energy (of which GTO is a part) was a principal internal advisor. DOE’s U.S. Energy Information Administration, Office of Fossil Energy, and Western Area Power Administration provided review and input. DOE also coordinated review with other federal agencies, such as the White House Office of Management and Budget, Department of the Interior (U.S. Geological Survey, Bureau of Land Management, and U.S. Fish and Wildlife Service), Department of Agriculture (U.S. Forest Service), Department of Defense (U.S. Navy), and the U.S. Environmental Protection Agency. The final version of this document was prepared by DOE. The framework for the *GeoVision* analysis collaboration—including compliance with the Office of Management and Budget’s Information Quality Act, or IQA—is illustrated in Figure D-1.



*Other Federal Agencies: Department of Interior, Bureau of Land Management, United States Geological Survey, United States Fish and Wildlife Service, Department of Defense, Environmental Protection Agency, United States Department of Agriculture, and United States Forest Service

Note: National laboratories are defined in Appendix A.

Figure D-1. Framework of the interaction of parties involved in the formation and execution of the *GeoVision* analysis

The following sections acknowledge specific contributors to the *GeoVision* project management and coordination (Section D.1); report authorship, editing, content development (Section D.2); task force contributors (Section D.3); and senior peer and external reviewers (Section D.4). Where applicable, main advisors and lead contributors are indicated by parentheses after the contributor’s name. GTO offers sincere thanks to all participants, who were instrumental in the development of the *GeoVision* analysis and the resulting report.

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Elisabet Metcalfe	U.S. Department of Energy
Dev Millstein	Lawrence Berkeley National Laboratory
Angel Nieto	Allegheny Science and Technology
Alexandra Prisjatschew	Allegheny Science and Technology

Joelynn Schroeder	National Renewable Energy Laboratory
Morgan Smith	Formerly BCS Inc.
Holly Thomas	U.S. Department of Energy
Linh Truong	National Renewable Energy Laboratory
Michael Weathers	U.S. Department of Energy
Dan Wendt	Idaho National Laboratory
Katherine Young	National Renewable Energy Laboratory
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D.3 *GeoVision* Project Task Forces

Electricity Potential to Penetration Task Force

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Nate Blair	National Renewable Energy Laboratory
Jonathan Ho	National Renewable Energy Laboratory
Anna Wall	Formerly National Renewable Energy Laboratory

Environmental and Social Impacts Task Force

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Holly Thomas (DOE Task Force Manager)	U.S. Department of Energy
Annika Eberle	National Renewable Energy Laboratory
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Seongeun Jeong	Lawrence Berkeley National Laboratory
David Keyser	National Renewable Energy Laboratory
Jordan Macknick	National Renewable Energy Laboratory
James McCall	National Renewable Energy Laboratory
Scott Nicholson	National Renewable Energy Laboratory
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Hybrid Systems Task Force

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Josh Mengers (DOE Task Force Manager)	U.S. Department of Energy
Mark Bearden	Pacific Northwest National Laboratory
Casie Davidson	Pacific Northwest National Laboratory
Ghanashyam Neupane	Idaho National Laboratory
Richard Zheng	Pacific Northwest National Laboratory

Institutional and Market Barriers Task Force

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Jeff Cook	National Renewable Energy Laboratory
Donna Heimiller	National Renewable Energy Laboratory
Jonathan Ho	National Renewable Energy Laboratory
Aaron Levine	National Renewable Energy Laboratory

Reservoir Maintenance and Development Task Force

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Zachary Frone (DOE Task Force Manager)	Oak Ridge Institute for Science and Education
Charles Carrigan	Lawrence Livermore National Laboratory
Thomas Corbet	Sandia National Laboratories
Christine Doughty	Lawrence Berkeley National Laboratory
John Finger	Retired, Sandia National Laboratories
Adam Foris	Sandia National Laboratories
Mack Kennedy	Lawrence Berkeley National Laboratory
Stephen Pye	Independent Consultant
Eric Sonnenthal	Lawrence Berkeley National Laboratory

Resource Exploration and Confirmation Task Force

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Anna Wall	Formerly National Renewable Energy Laboratory
Chester Weiss	Sandia National Laboratories

Thermal Applications Task Force

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Nate Blair	National Renewable Energy Laboratory
Michael Gleason	Formerly National Renewable Energy Laboratory

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Kevin McCabe	National Renewable Energy Laboratory
Meghan Mooney	National Renewable Energy Laboratory
Michael Rossol	National Renewable Energy Laboratory
Ben Sigrin	National Renewable Energy Laboratory
Laura Southard	Oklahoma State University
Jeffrey Spitler	Oklahoma State University
Joseph Warner	University of Tennessee
Katherine Young	National Renewable Energy Laboratory

D.4 *GeoVision* Analysis Report Review

Senior Peer Reviewers (Visionaries)

Pierre Audinet	World Bank Group
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Yoram Bronicki	Independent Geothermal Consultant
Wendy Calvin	University of Nevada, Reno
Richard Campbell	Tetra Tech
Louis Capuano Jr.	Capuano Engineering
Halley Dickey	Industrial Builders Inc.
Jack DiEnna	Geothermal National & International Initiative
Doug Dougherty	Geothermal Exchange Organization
Karl Gawell	Formerly Geothermal Energy Association
Doug Glaspey	U.S. Geothermal, Inc.
Roland Horne	Stanford University
Josh Nordquist	Ormat
David Olsen	California Independent System Operator (CAISO) Board of Governors
Steve Ponder	Formerly Geothermal Resources Council
Ann Robertson-Tait	Schlumberger
Jefferson Tester	Cornell University
Paul Thomsen	Ormat (Formerly Nevada Public Utilities Commission)
Robert Tucker	Global Power Solutions
Colin Williams	U.S. Geological Survey

External Reviewers

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Michael Albrecht	TBA Power, Inc.
Rosalind Archer	NZ Oil and Gas/University of Auckland
Bridget Ayling	Great Basin Center for Geothermal Energy
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Stephen Batstone	Whiteboard Energy
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Greg Bignall	GNS Science
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Gordon Bloomquist	Independent Consultant
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Rod Colwell	Controlled Thermal Resources
David Danielson	Breakthrough Energy Ventures
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William Harvey	POWER Engineers
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Jennifer Livermore	Solstice Geothermal
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Patrick Mills	Confederated Tribes of the Umatilla Indian Reservation
Greg Mines	Independent Consultant
Joseph Moore	Energy and Geoscience Institute
Susan Petty	AltaRock Energy
Morgan Snyder	Walton Family Foundation
Andrew Stumpf	Illinois State Geological Survey
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