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).

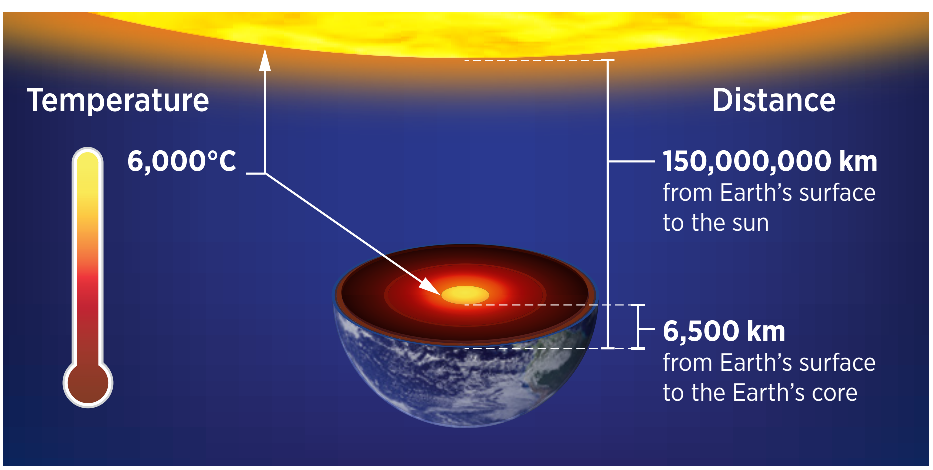


Figure 2-1. A conceptualized cut-away of the Earth, showing temperature increasing with depth to the Earth's core, where the temperature is similar to the sun

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).

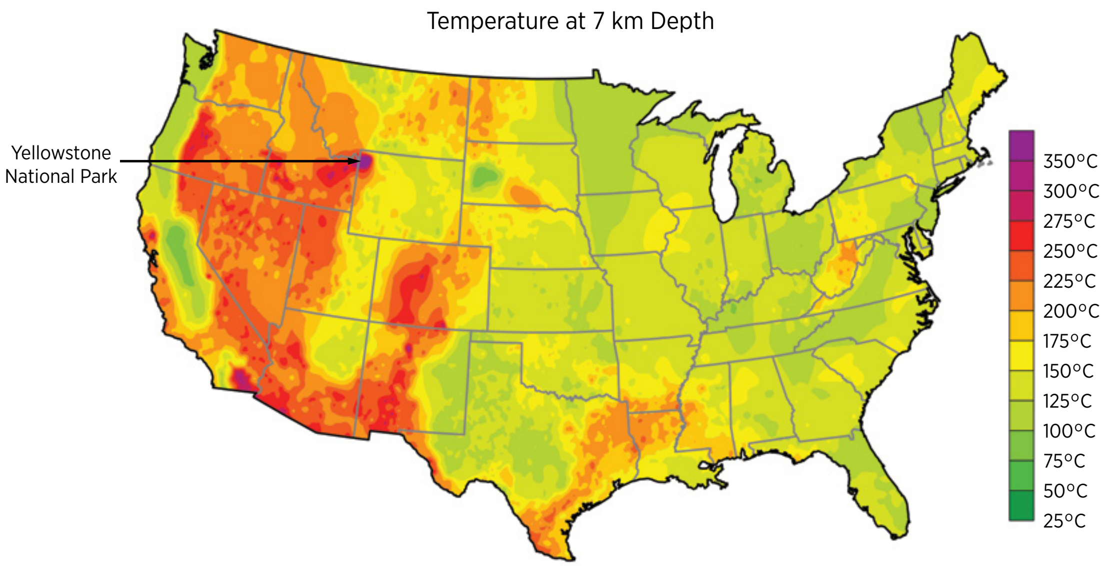


Figure 2-2. Temperatures throughout the contiguous United States at a depth of 7 km (about 4 miles)

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]

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

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.

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

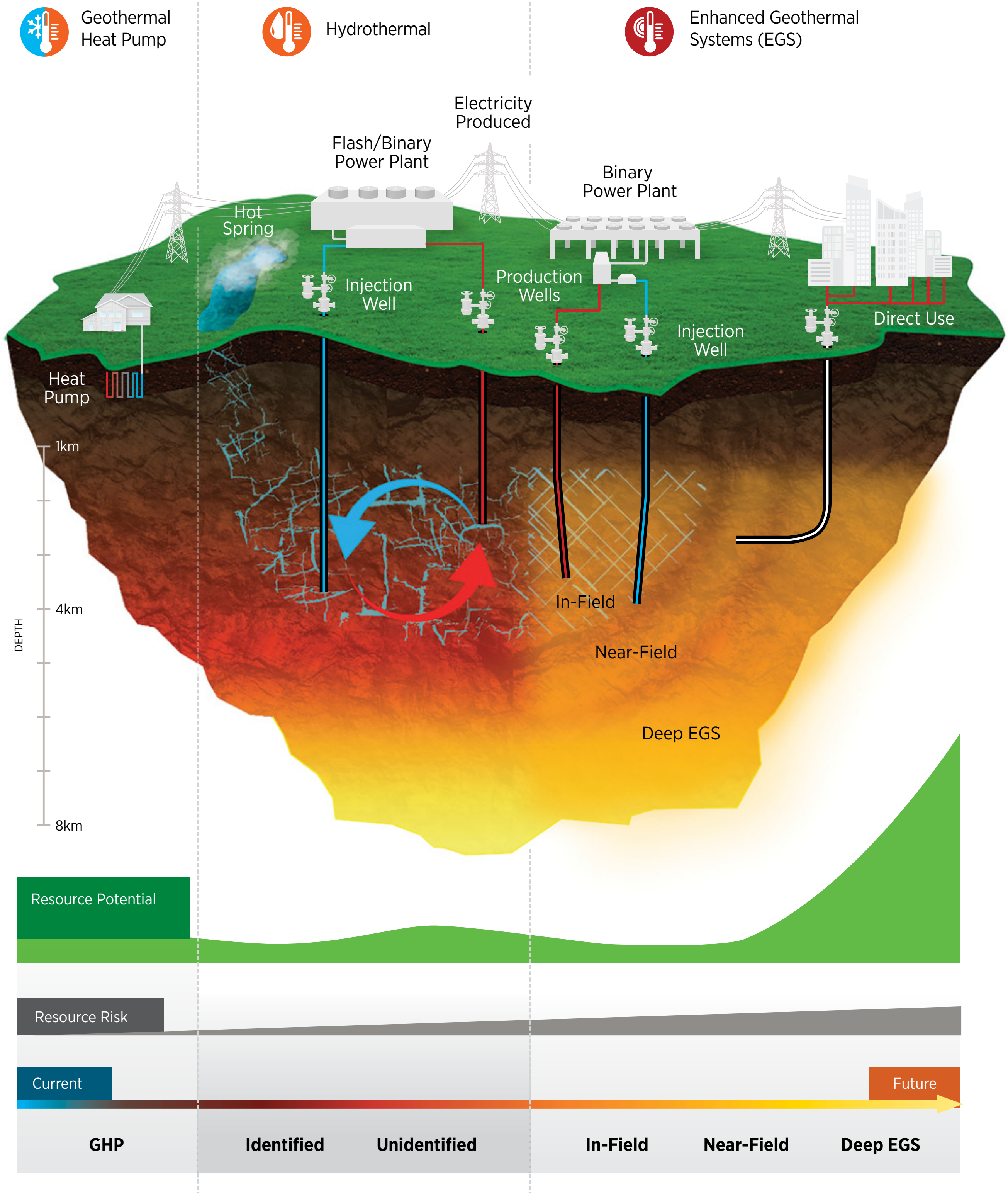


Figure 2-3. The diversity of geothermal resources and applications, delineated within three resource categories: geothermal heat pump, hydrothermal, and enhanced geothermal systems

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.

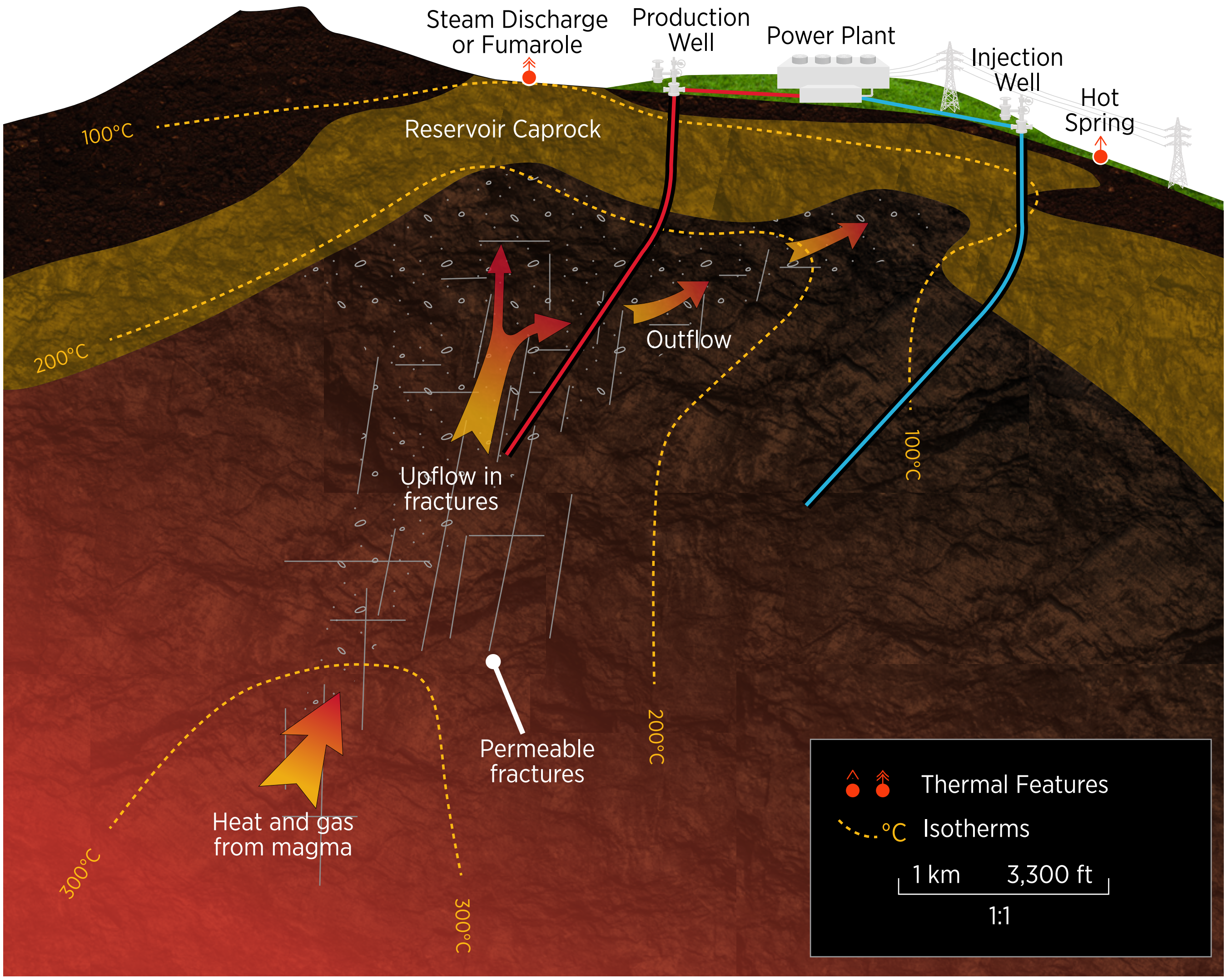


Figure 2-4. Idealized cross-section of a hydrothermal resource showing various conceptual elements of a high-temperature hydrothermal reservoir

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.

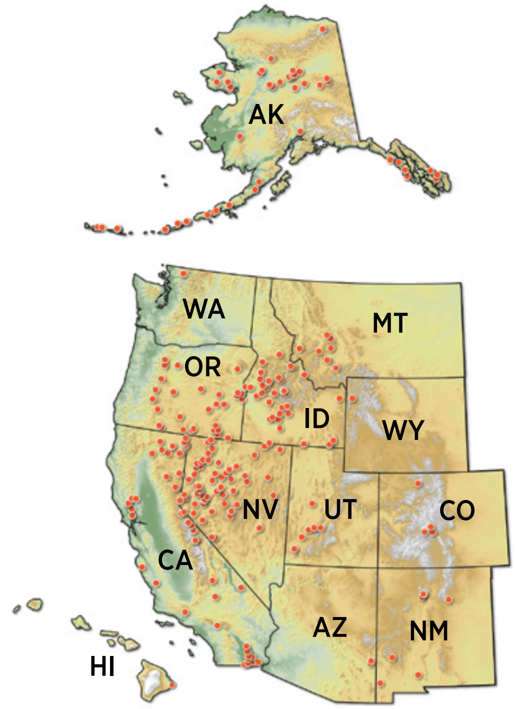


Figure 2-5. Map illustrating the location of identified hydrothermal resources in the United States (represented by the red dots) included in the 2008 U.S. Geological Survey geothermal resource assessment

Source: Williams et al. 2008b

The U.S. Geological Survey (USGS) resource assessment estimates that the *identified* hydrothermal resources of >90°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°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 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°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 temperatures[25]—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

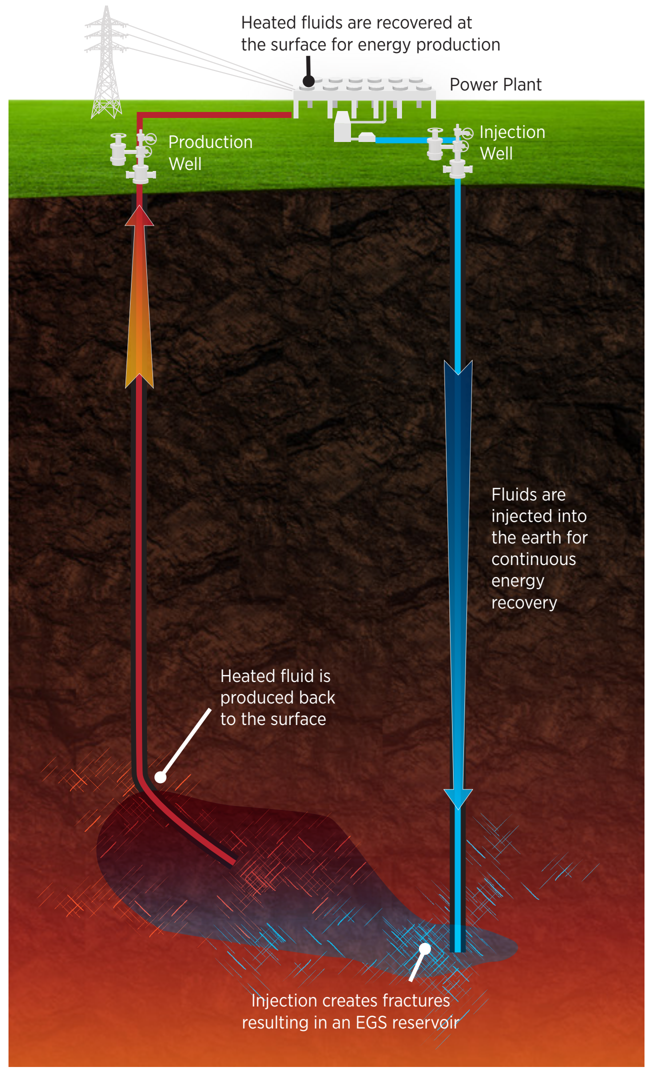


Figure 2-6. Conceptualization of an enhanced geothermal system

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 *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.

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.

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.


Geothermal steam turbine blades. *Photo credit: Betsy Phillips*

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 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.

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

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.

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 GWh_{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.

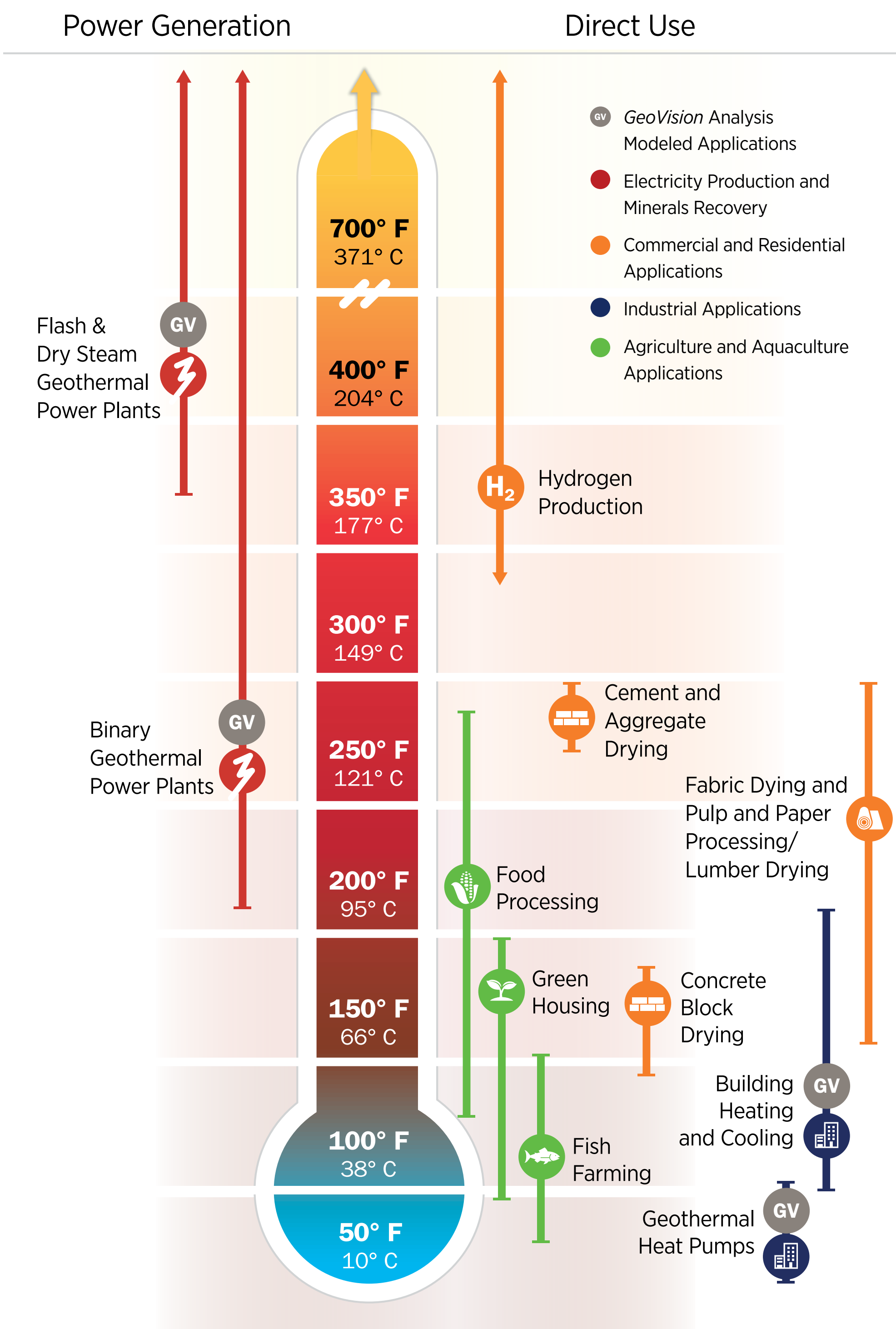


Figure 2-7. The continuum of geothermal energy technology applications and uses

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.

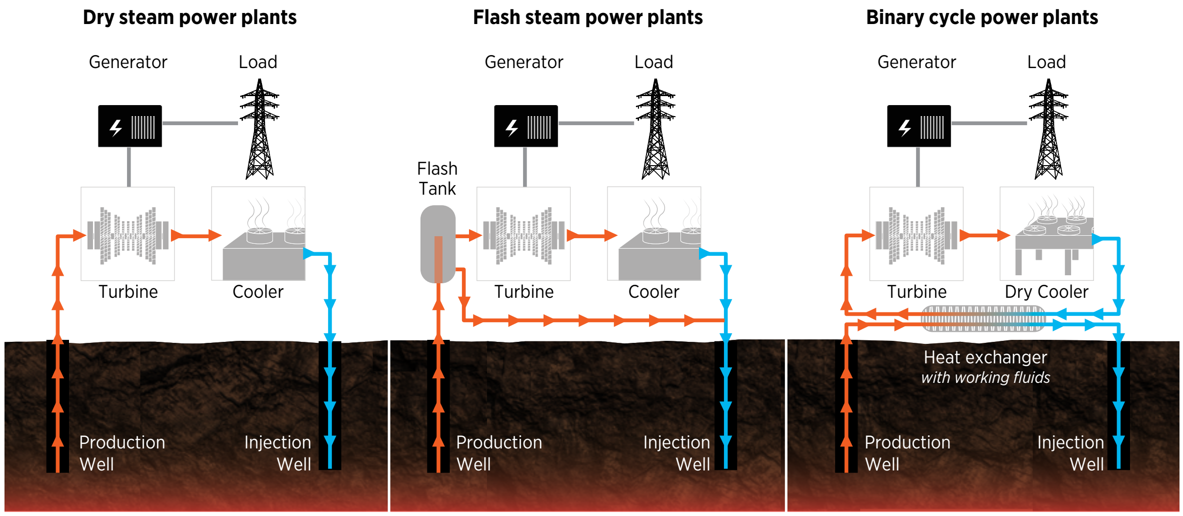


Figure 2-8. Geothermal power-plant configurations: dry steam, flash steam, and binary cycle

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).

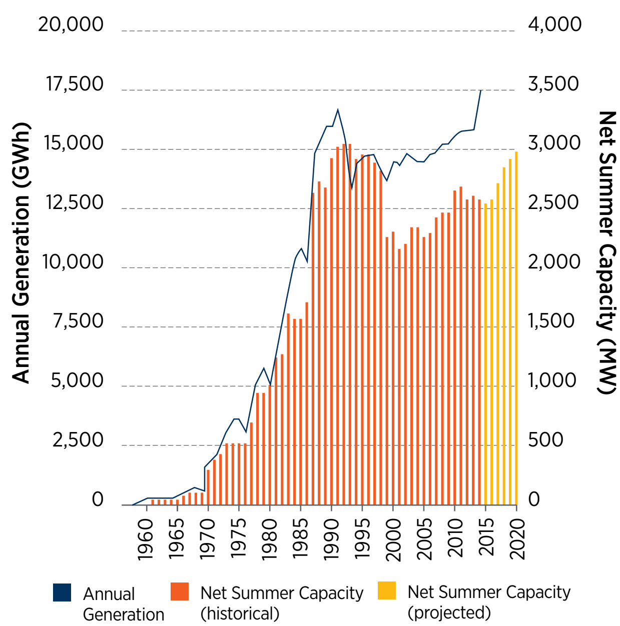


Figure 2-9. U.S. historical annual geothermal electricity generation (in GWh_e) and installed net summer capacity (in MW_e)

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.

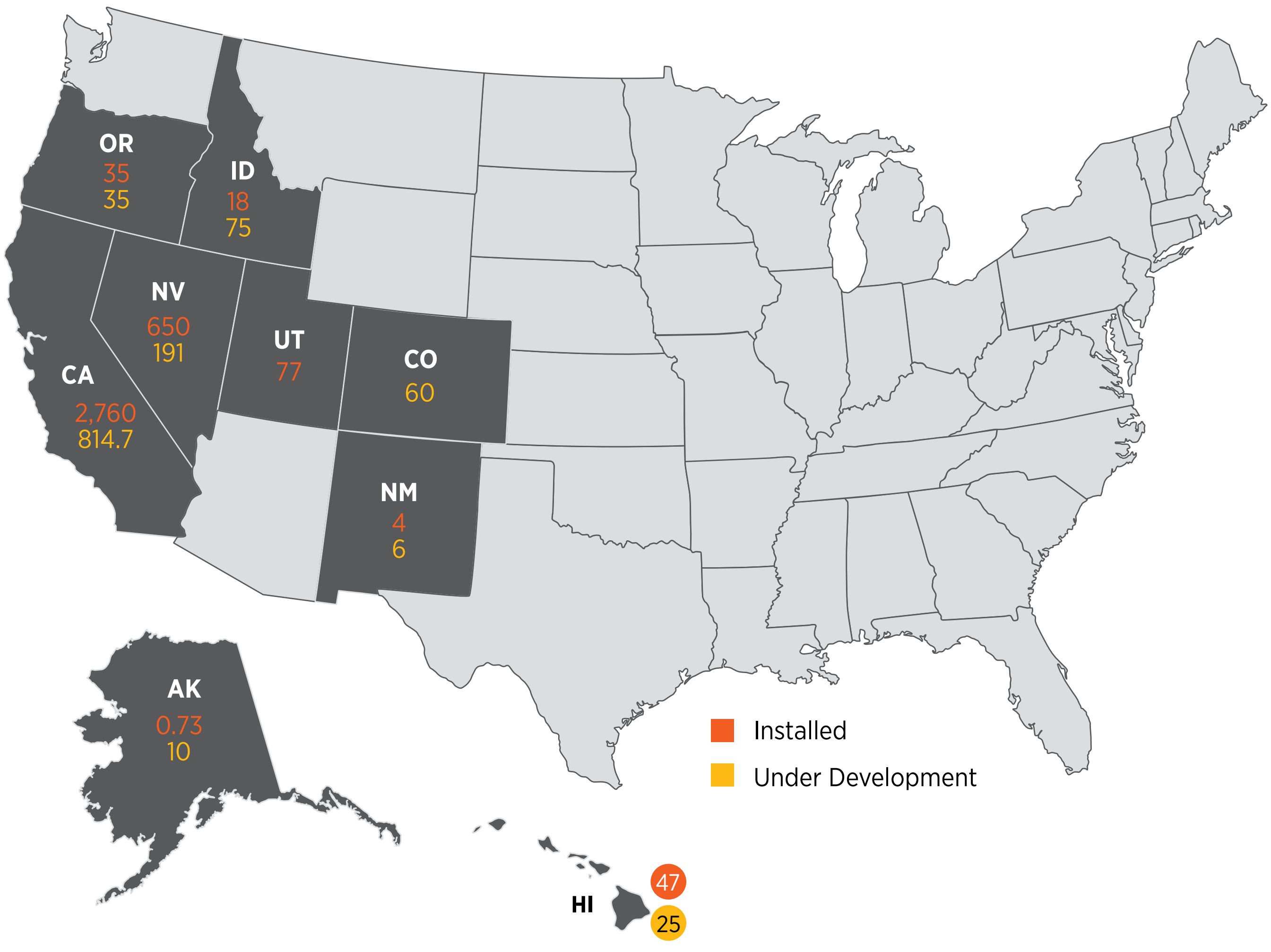


Figure 2-10. Existing and planned U.S. geothermal installed capacity (MW_e) by state

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 m^2 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.

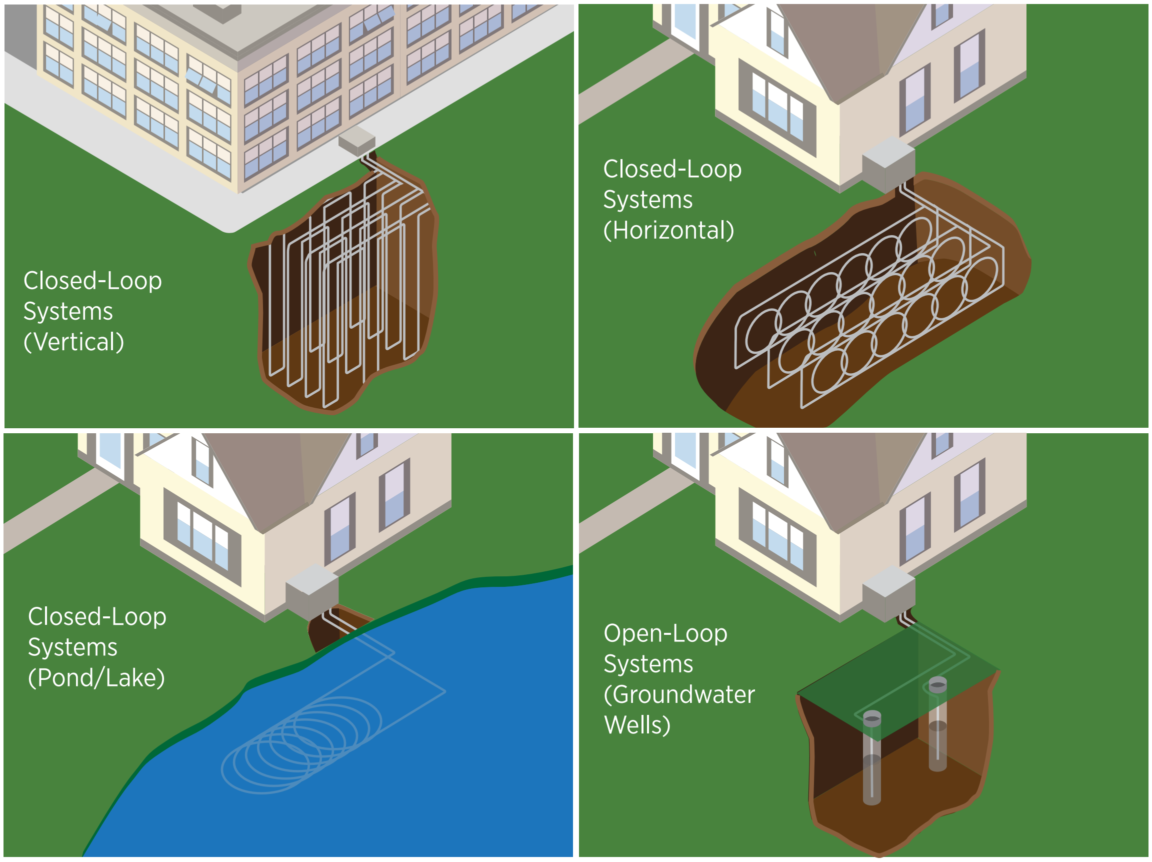


Figure 2-11. Illustrations of commonly used closed-loop and open-loop ground heat exchangers

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.

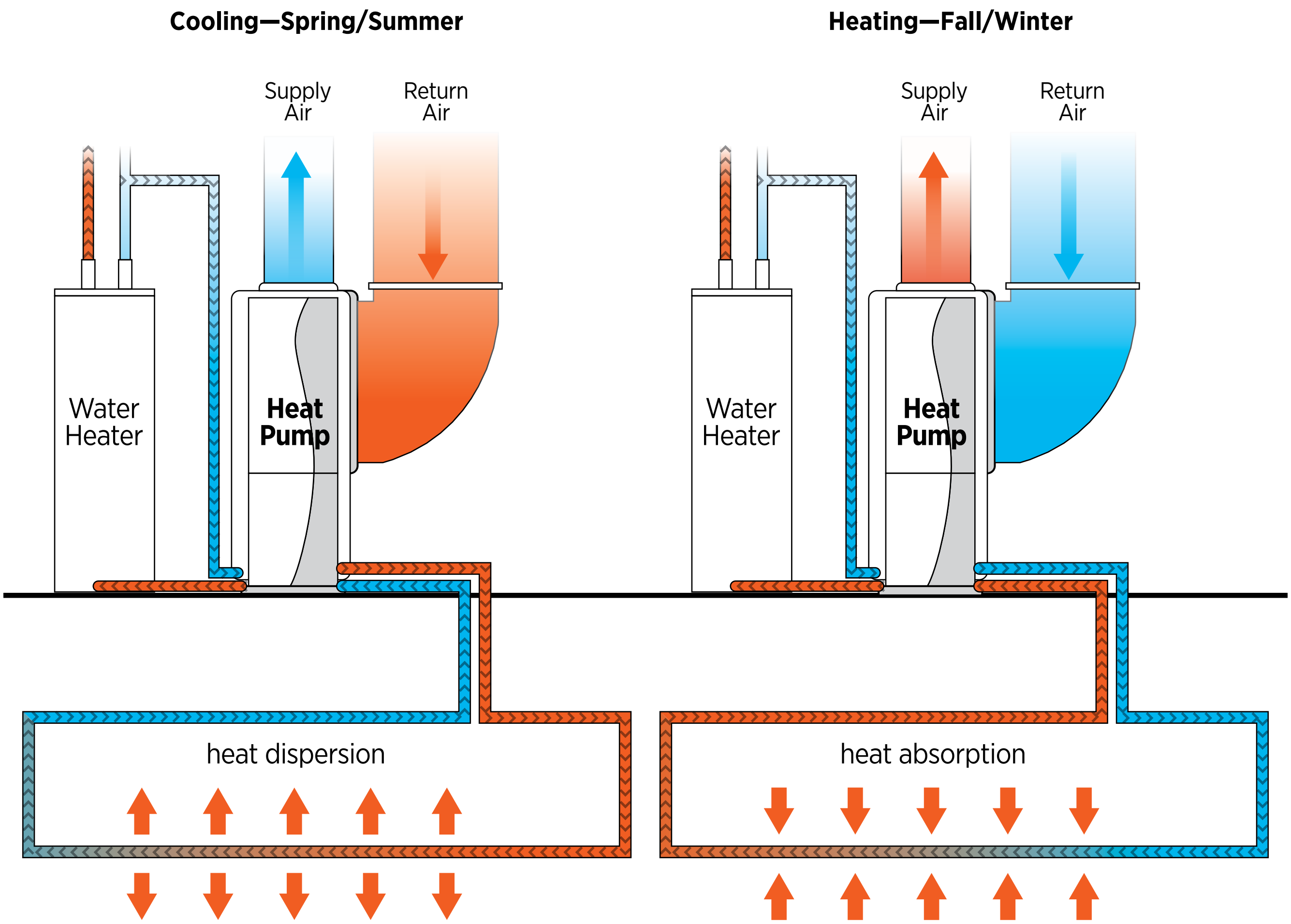


Figure 2-12. Schematic of a geothermal heat pump showing the simplified ground heat-exchanger loop, heat pump, and indoor delivery system

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.

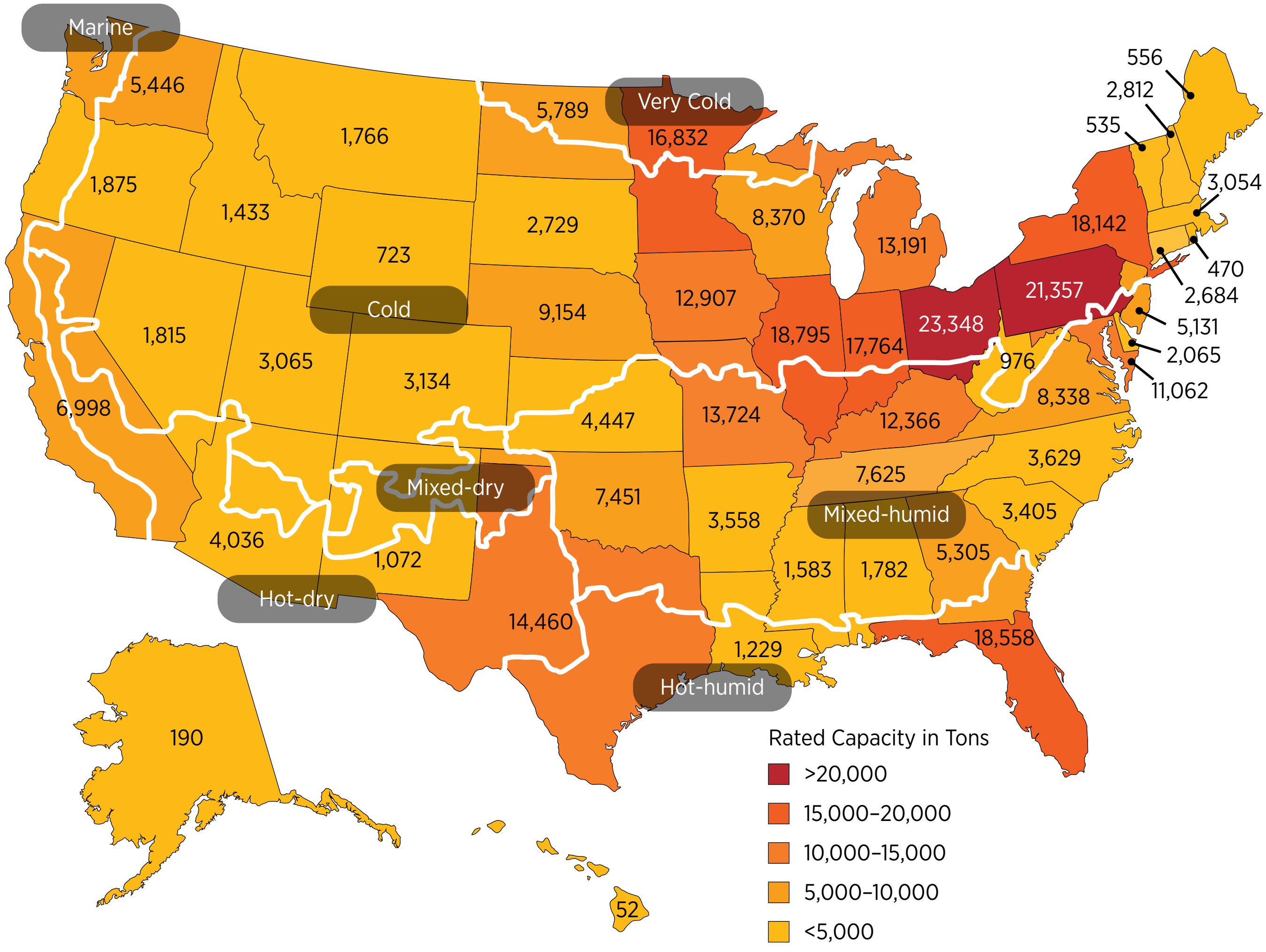


Figure 2-13. U.S. geothermal heat-pump shipments (rated capacity in cooling tons) in 2009

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.

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

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 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 factor[39] 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.

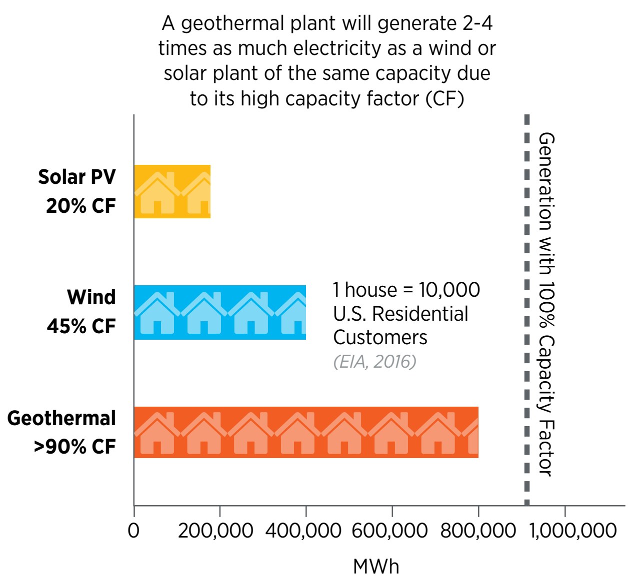
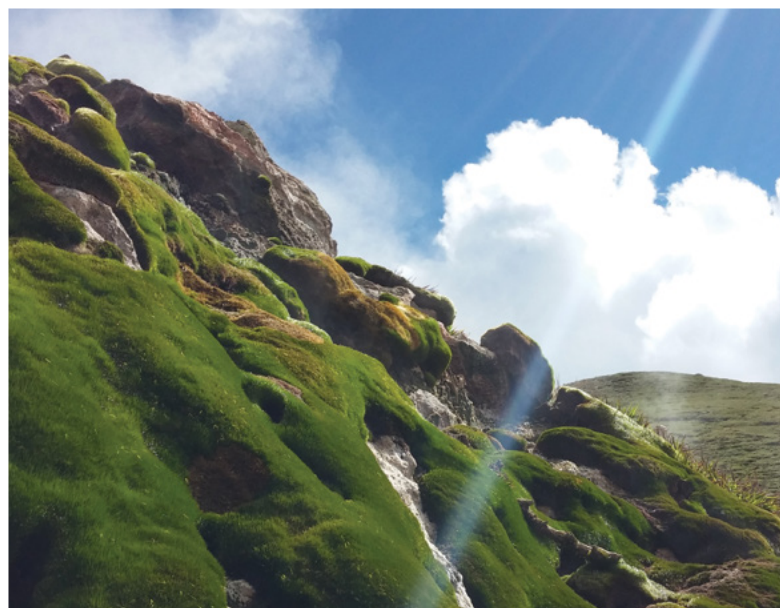


Figure 2-14. Capacity factors for geothermal, wind, and solar photovoltaic indicating annual generation (MWh_e) from equivalent 100-MW_e nameplate-capacity power plants

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).

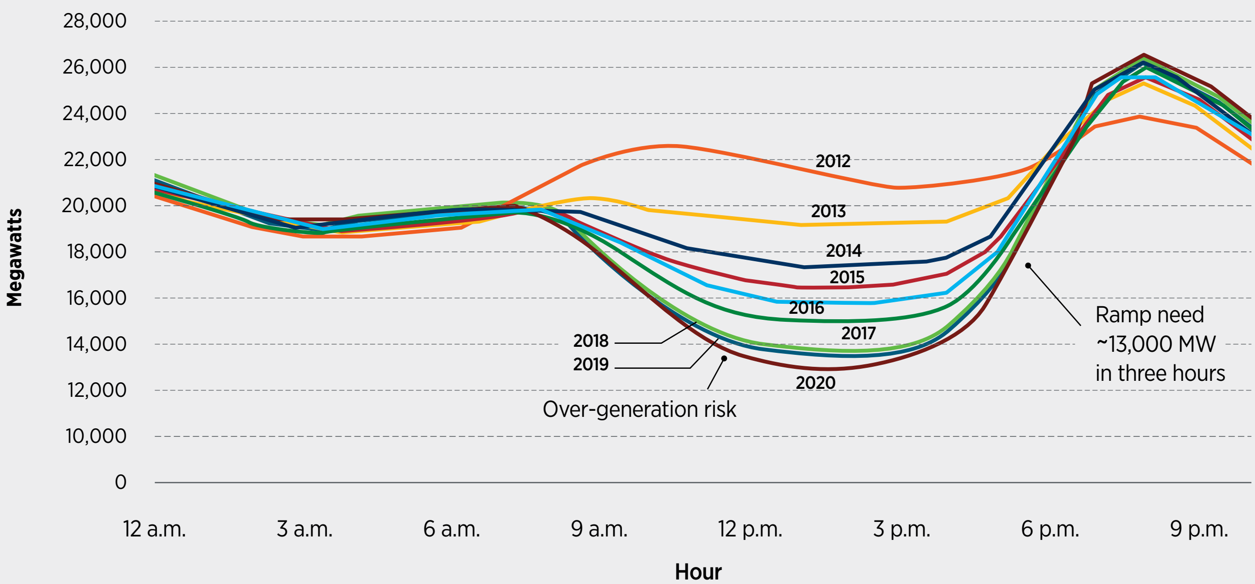


Figure 2-15. Past and projected net-load profiles to 2020 on a typical spring day in California, illustrating the "duck-curve" effect with steep ramping needs and over-generation risk

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-MWe 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 m^2 per GWh_e, which is less than coal (3,642 m^2), wind (1,335 m^2), or solar photovoltaic (3,237 m^2) (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).

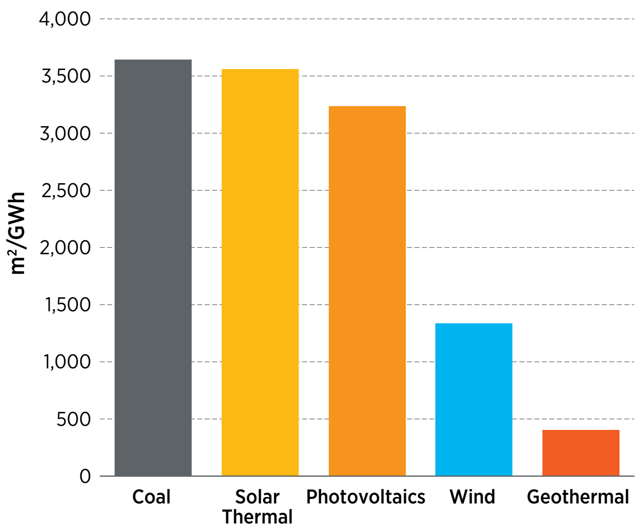


Figure 2-16. Land footprint by GWh$_e$ for various electricity-generation technologies

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 performance[42] 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).

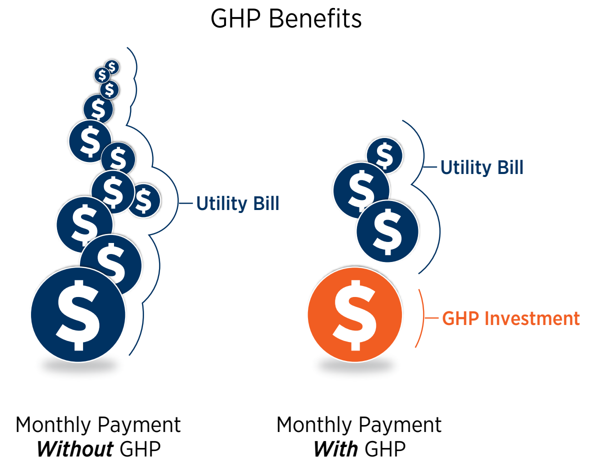


Figure 2-17. A conceptual illustration of potential consumer savings with geothermal heat pumps

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-sized[45] 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 development[47] in that each requires creating and sustaining a functional resource by using reservoir stimulation technologies. However, 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.

> 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.

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,

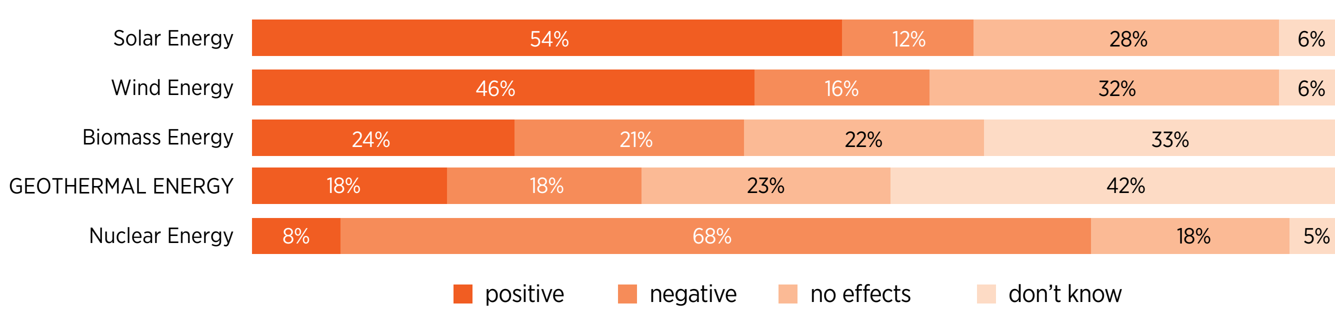


Figure 2-18. Acceptance of renewable energy technologies based on a social acceptance survey conducted in Italy by Pellizzone et al. (2015)

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 (Linvill 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 GW_e of renewables were procured under California's renewable portfolio standard from 2003 to 2013, yet only 100 MW_e (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 tiering[52] 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 activity[56] 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 land[57] 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]

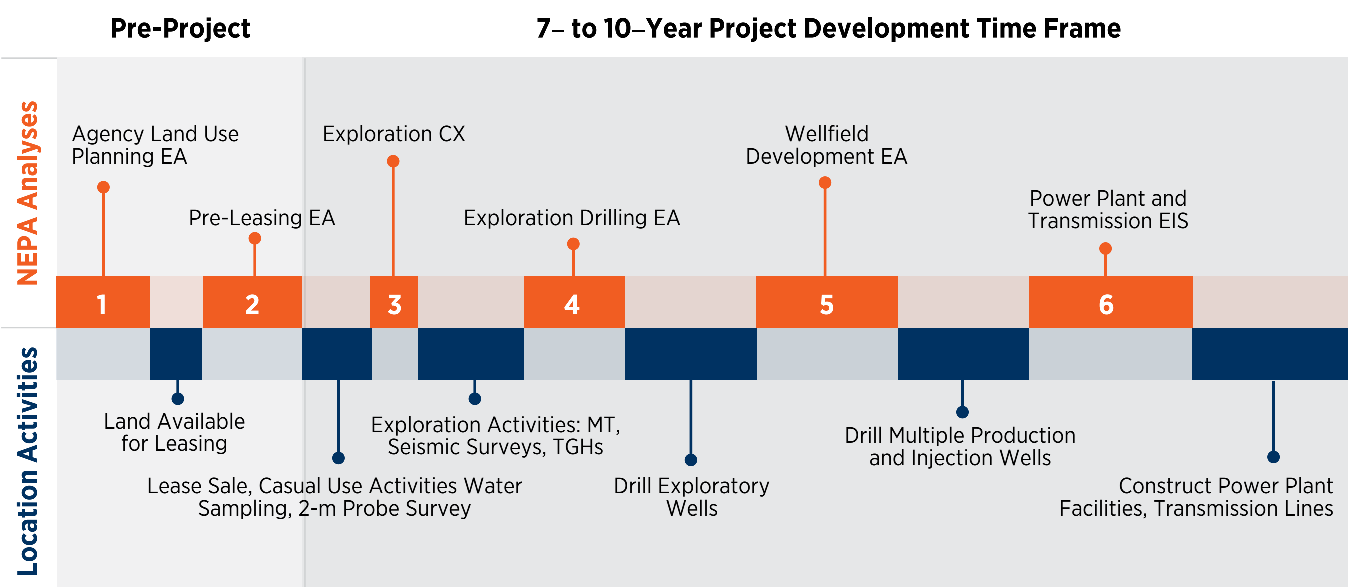


Figure 2-19. Example timeline of a geothermal project on federal lands, illustrating that a single location could trigger National Environmental Policy Act analysis six separate times

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 regulations[61] 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 exiting 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).