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Water Resource Assessment of Geothermal Resources and Water Use in Geopressured Geothermal Systems

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Environmental Science Division

The authors acknowledge and are grateful for the expert assistance of Gregory Mines, Idaho National Laboratory; A.J. Mansure, Geothermal Consultant; Chad Augustine, National Renewable Energy Laboratory; and Scott Schlueter, James Kuiper, Shabbir Shamsuddin, and Michael McLamore, Argonne National Laboratory in our data-gathering and analysis efforts; and Michael Wang, Argonne National Laboratory, for managing the project. We also thank our sponsor, Arlene Anderson of the Office of Geothermal Technologies, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy.

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ACRONYMS AND ABBREVIATIONS

EGS	enhanced geothermal systems
GETEM	Geothermal Electricity Technology Evaluation Model
LCA	life cycle analysis
LCOE	levelized cost of electricity
NEMS	National Energy Modeling System
NREL	National Renewable Energy Laboratory

EXECUTIVE SUMMARY

With a potential threefold increase in geothermal electricity generation by 2035, geothermal energy is increasingly recognized for its potential to reduce carbon emissions (EIA 2011a). Energy and environmental analyses are critical to developing a robust set of geothermal energy technologies that meet future demand. Previous work has summarized what is currently known about the life-cycle fresh water requirements of geothermal power-generating systems and the water quality of geothermal waters. This report builds upon that work, presenting an assessment of fresh water demand for future growth in utility-scale geothermal power generation and an analysis of fresh water use in low-temperature geopressured geothermal power generation systems. This is part of a larger effort to compare the life-cycle impacts of geothermal electricity generation with other power generation technologies.

This report is organized with an introduction followed by two primary analysis sections. The introduction gives the background of the project and its purpose and summarizes the geothermal electricity generation technologies evaluated in this study. These technologies include conventional hydrothermal flash and binary systems, enhanced geothermal systems (EGS), and geopressured geothermal systems.

Part I is the assessment of water demand for future growth in deployment of utility-scale geothermal power generation. The approach combines a geothermal supply curve with an analysis of life-cycle water consumption for geothermal systems and presents consumption information according to resource type, levelized cost of energy (LCOE), and potential growth scenarios. Four resource types were considered: identified hydrothermal, unidentified hydrothermal, near-field EGS, and deep EGS. Near-field EGS resources can significantly impact overall water demand for geothermal resources despite contributing a relatively small percentage of the potential generation capacity in most states evaluated. Similarly, as the electricity generation potential increases along the supply curve, the potential water consumption increases at a faster rate because the more capital and water-intensive EGS technologies can be developed at higher costs. When realistic geothermal growth scenarios were analyzed to evaluate the relative amount of additional water demand compared with additional electricity generation, the results were mixed. In some states the growth in power generation exceeded the growth in water consumption, resulting in a decline in overall water intensity of electricity generation, while in others the opposite was true. In cases where growth in geothermal increased the water intensity of electricity generation, it was observed that baseline water intensity was already significantly below the national average.

Part II is the analysis of water consumption in low-temperature geopressured geothermal power generation over the life cycle of the plant. Water consumption refers to the water that is withdrawn from a resource such as a river, lake, or nongeothermal aquifer that is not returned to that resource. Thermal electric power generation assumes an air-cooled binary system, which is modeled using DOE's Geothermal Electricity Technology Evaluation Model (GETEM; DOE 2011).

On a per-well basis and a per-kilowatt-hour lifetime energy output basis, geopressured geothermal systems appear to consume less water than other geothermal technologies. Overall

water requirements across the lifetime are low, because maintaining reservoir pressure is not a long-term goal of geopressured systems. As a result, the spent geofluid is typically sent to a disposal well, although opportunities for reuse of the geofluid should be explored.

As geothermal electricity generation continues to grow, it will be important to explore alternatives to fresh water resources that are available to meet increased water demand. In addition to geofluid reuse from geopressured geothermal resources, other sources explored include water produced from oil and gas activities, water extracted from carbon capture and sequestration projects, and saline groundwater resources.

1 INTRODUCTION

The Energy Information Administration of the U.S. Department of Energy projects that renewable electricity, which now represents around 12.8% of U.S. electricity generation, will increase to 15 to 20% by 2035 (DOE 2011). While most of the increase in renewable electricity is projected to come from wind turbines and biomass combustion plants, geothermal electricity generation is projected to increase threefold as a result of technology advances that make more sites attractive for development and increase the available resources at existing geothermal sites (EIA 2011a). Geothermal power, customarily associated with states with conspicuous geothermal resources (e.g., geysers or fumaroles), could grow even more if enhanced geothermal systems (EGS) and low-temperature resources prove to be cost effective and environmentally benign. Coupling this with the fact that geothermal plants tend to run near their full capacities for most of their lifetimes, geothermal power could become a viable option for many states and, in the process, become a significant contributor to the U.S. power infrastructure.

1.1 PURPOSE

This work is part of a larger project by Argonne National Laboratory in support of the Geothermal Technologies Program of DOE's Office of Energy Efficiency and Renewable Energy to compare the energy and environmental impacts of geothermal technologies with competing technologies for electricity generation (see also Clark et al. 2011). The results in Clark et al. (2011) are further evaluated here to assess the impact of future geothermal growth. Additionally, Argonne carried out a life cycle analysis (LCA), reported in a companion document (Sullivan et al. 2010), to quantify energy and environmental benefits of geopressured geothermal systems by examining proximity to infrastructure, resource availability, and tradeoffs associated with well depth and resource temperature. This report summarizes the LCA effort as it pertains to water use in geopressured power plants.

The scope of this work is limited to the quantification of on-site water requirements to construct and operate geothermal power plants. While materials for the construction of geothermal power plants have upstream water burdens embedded in industrial processes and energy consumption, their water impacts are not necessarily allocated to the watershed or aquifers associated with a power plant and are not included in this analysis.

1.2 OVERVIEW OF STUDY

With significant potential growth opportunities for geothermal technologies, it is important to understand their material, energy, and water requirements and potential environmental impacts. We have conducted life cycle energy and greenhouse gas emissions simulations for EGS, hydrothermal flash, hydrothermal binary, and geopressured-geothermal power-generating technologies for scenarios developed with input from subject matter experts. Argonne's GREET model was expanded to address life-cycle emissions and energy issues so that reductions in fossil energy use, petroleum use, greenhouse gas emissions, and criteria air pollutant emissions by EGS could be thoroughly examined by stakeholders. As the inventory for this analysis was conducted, water use associated with the process was also quantified. The results of the water inventory were presented in Clark et al. (2011), with the exception of geopressured geothermal systems, which are presented here, in Part II. The results presented in Clark et al. (2011) were further analyzed to explore the potential demand for water according to future growth scenarios. The results of that effort are discussed in Part I.

1.3 GEOTHERMAL TECHNOLOGIES

Several geothermal technologies are evaluated in this report. This section briefly describes the different types of systems considered and their water-use patterns in geothermal electricity production.

1.3.1 Conventional Hydrothermal Flash System

Hydrothermal fluids above 182°C (360°F) can be used in flash plants to produce electricity (USDOI & USDA 2008). For the purposes of this assessment, temperatures between 175°C and 300°C were considered. The geofluid is rapidly vaporized or “flashed,” either as it ascends from the well or at the plant, where the geofluid flows into a tank held at a much lower pressure. The vapor drives a turbine, which then drives a generator. Any liquid that remains in the tank can be flashed again in a second system to generate more electricity. The vapor from these systems is typically released to the atmosphere while the condensate is injected into an underground reservoir.

1.3.2 Conventional Hydrothermal Binary System

Energy can be extracted in binary-cycle power plants from geothermal reservoirs with moderate temperatures between 74°C and 182°C (USDOI & USDA 2008). Geofluid temperatures between 150°C and 185°C are considered for this LCA. In binary-cycle plants, geothermal fluid is pumped from a well and flows through a heat exchanger to warm a secondary fluid, which is often referred to as the “working fluid.” The working fluid has a much lower boiling point than the geofluid. Common working fluids include isobutane and isopentane. The heat from the geofluid causes the working fluid to flash to vapor, which then drives a turbine. The vapor is then condensed for reuse. Because it is a closed-loop system, virtually nothing is emitted into the atmosphere. Moderate-temperature water is by far the more common geothermal resource; thus, most geothermal power plants in the future will be binary-cycle plants.

1.3.3 Enhanced Geothermal System

EGS can expand the electricity-generating capacity of geothermal resources. By injecting water into the subsurface resource, existing fractures can be expanded or new fractures can be created to improve water circulation through the resource. These systems can be implemented in formations that are dryer and deeper than conventional geothermal resources (DOE 2008). Temperatures considered for this LCA are between 175°C and 225°C. EGS relies on binary system technology, which recirculates geofluid, to maintain reservoir pressure and open fractures. Because of the increased depths and temperatures and decreased water availability of the resources involved, environmental impacts from EGS can be different from conventional geothermal power plants.

1.3.4 Geopressured Geothermal System

Geopressured geothermal power plants take advantage of underground pressurized reservoirs that contain both hot water and dissolved natural gas. The resource base includes thermal energy, mechanical energy, and chemical energy (in the form of methane). The first hybrid geopressured geothermal power plant in the U.S., Pleasant Bayou in Brazoria County, Texas, generated electricity from the geofluid and separated the natural gas to test both the production of electricity from combustion in an on-site hybrid power system and processing the natural gas to direct-to-sales pipelines (DOE 2010; Randolph et al. 1992). The dissolved gas and any free gas is separated from the geofluid prior to directing the geofluid through a binary system.

2 PART I: WATER RESOURCE ASSESSMENT

2.1 INTRODUCTION

A recent life cycle analysis (LCA) of water requirements for geothermal electricity production found geothermal technologies to be low relative to most conventional generation technologies (Clark et al. 2011). However, the most promising geothermal resources tend to be in fresh-water-stressed areas. The purpose of this water resource assessment is to estimate expected water demand from future growth in geothermal electricity generation by state and put it in the context of existing power generation and water demand. This analysis will help identify any areas where growth in geothermal production may be slowed by limitations on water availability.

2.2 APPROACH AND METHODS

This analysis leverages two recent research efforts funded by the DOE Geothermal Technologies Program to estimate future water demand resulting from growth in geothermal energy production. The approach combines a geothermal supply curve developed by the National Renewable Energy Laboratory (NREL) with an analysis of life-cycle water consumption for geothermal systems performed by Argonne National Laboratory (Augustine et al. 2010; Clark et al. 2011).

2.3 WATER CONSUMPTION ESTIMATES

NREL has developed a detailed supply curve for future geothermal energy development. Geothermal resources are broken down into four resource categories: identified hydrothermal, unidentified hydrothermal, near-field enhanced geothermal systems (EGS), and deep EGS. Identified hydrothermal resources are resources known to exist and be capable of supporting hydrothermal geothermal power systems. Unidentified hydrothermal resources are resources that are likely to exist but have not been verified. Near-field EGS resources are associated with identified hydrothermal resources but may require additional hydraulic stimulation to be exploited. Deep EGS resources are hot rock formations found at depths greater than 4 km and require hydraulic stimulation to create fractures for fluid circulation for power generation. Geothermal resources in sedimentary formations were included within the deep EGS category and were not considered separately. Co-production of geothermal power from oil and gas wells and from geopressured resources was not considered in this analysis, but will be considered for future studies as data about the availability of these resources improves. On the basis of what was known about the resources, NREL used the Geothermal Electricity Technology Evaluation Model (GETEM; DOE 2011) to model the electricity generation capacity (MWe) and estimate the levelized cost of electricity (LCOE, \$/kWh).

LCOE was estimated for two scenarios: (1) a base case with minimal technological improvements, and (2) a target case that assumed a reduction in cost of EGS systems due to continued federal investment in research, development, and demonstration (Augustine et al.

2010). These two sets of LCOE values were used to develop two separate supply curves that are used throughout this analysis and are referred to as “base” and “target” throughout this section.

Argonne has estimated life-cycle water consumption for three different types of geothermal facilities: a hydrothermal flash plant, a hydrothermal binary plant, and an EGS system (Clark et al. 2011). The analysis defines water consumption as freshwater consumed, and it does not include the loss of geofluid. Evaporative losses of geofluid can be very significant in flash systems, which can have important impacts on reservoir sustainability; however, long term reservoir sustainability is not considered in this study. The average water consumption values for each system are shown in Table 1. These water consumption values are then matched with the resource classifications within the NREL geothermal supply curve.

The supply curve specifies whether a given resource is likely to be exploited with a binary or flash system, depending on whether the resource temperature is above or below 225°C. For all hydrothermal resources (both identified and unidentified), water consumption for flash systems is based on the Argonne hydrothermal flash scenario, and for binary systems it is based on the Argonne hydrothermal binary scenario. The hydrothermal flash scenario assumes use of the condensate from the flash process is the primary source for evaporative-based cooling, while the hydrothermal binary scenario assumes air-based cooling. Not all geothermal plants conform with these assumptions because climate, water resource availability, and regulatory requirements vary from site to site.

For all EGS resources (including near-field EGS and deep EGS), water consumption is based on the Argonne EGS scenario with an air-cooled binary plant. The NREL supply curve analysis assumes flash plants would still be used for EGS resources over 225°C. This is thought to be an unlikely design choice for most EGS resources because of the inherent loss of reservoir fluid in flash systems. Due to this loss of fluid and their inherent low permeabilities and connectivities, EGS flash systems would almost certainly require a significant increase in water consumption for makeup water to maintain pressure and flow within the system. It is therefore assumed that most EGS resources will use binary systems, even if the resource temperature allows for the use of a flash system.

TABLE 1 Life-Cycle Water Consumption for Geothermal Systems

Argonne Water LCA System Designs	Water Consumption (gal/kWh)	NREL Geothermal Resources Assuming the Same Water Consumption
Hydrothermal flash	0.01	Identified hydrothermal flash, unidentified hydrothermal flash
Hydrothermal binary	0.27	Identified hydrothermal binary, unidentified hydrothermal binary
Enhanced geothermal systems	0.51	Near-field EGS, deep EGS

Source: Clark et al. (2011).

The values in Table 1 are used to calculate annual water consumption for all geothermal resources in the supply curve. Since geothermal electricity generation capacity is given in terms of MWe, a capacity factor of 90% relative to the rated capacity is assumed for all plants to determine the number of kWh per year produced for calculating annual water consumption (Lund et al. 2005). For the water resource assessment water consumption values are converted to acre-feet per year for easier comparison with existing data on water consumption at a state level.

2.4 GEOSPATIAL ANALYSIS

The combined data set was converted to work with ArcGIS mapping and geospatial analysis software. The resolution of location information available within the NREL supply curve data set for the geothermal resources varied depending upon the resource type. For identified hydrothermal and near-field EGS resources, specific latitude and longitude locations are given. Unidentified hydrothermal resources are specified at the state level. Deep EGS resources are specified by temperature and depth along the region code for both the National Energy Modeling System (NEMS) and MARKAL models. These region codes cover many states. For scenarios where deep EGS resources were included, the fraction of the resource in each state is estimated by comparing the given temperature and depth with temperature versus depth maps provided by Idaho National Laboratory and produced from data from Southern Methodist University (INL 2011). This allows for a range of scenarios to be developed and analyzed at a state level.

2.5 SCENARIO DEFINITIONS

A total of 13 GIS maps were generated for different scenarios representing varying levels of future growth in geothermal electricity generation. The scenarios are broken down into three main sets. Each set of scenarios is analyzed together to draw broad conclusions about its implications for geothermal water demand. The scenarios are summarized in Table 2.
The first set of scenarios looks at the total geothermal potential and water consumption for three different resource types: identified hydrothermal, unidentified hydrothermal, and near-field EGS. Deep EGS systems are not included in this set of scenarios because the deep EGS resource location data was not available at a state level for the entire supply curve. This set of scenarios allows for a direct comparison of geothermal potential and water demand based upon resource type.

The second set of scenarios includes all resources with an estimated LCOE below a given value. The LCOE values considered are \$0.05, \$0.10, \$0.15, and \$0.20 per kWh for both the base and target supply curves. This set of scenarios allows for analysis of trends in water demand and resource types as deployment proceeds along the supply curve with increasing costs. It also allows for comparison between different assumptions about future costs and technological improvements embedded in the base and target supply curves.

The final set of scenarios looks at results from the Energy Information Administration’s NEMS integrated energy model (EIA 2011b). The model is slightly modified to include the existing NREL geothermal supply curve. This version of the NEMS model is referred to as

NEMS-GPRA, for Government Performance and Results Act. The modeling was performed in 2010 by OnLocation, Inc., for the DOE Geothermal Technologies Program for its annual internal program analysis. The results, presented at the fiscal year 2010 4th-quarter meeting of the Geothermal Strategic Planning and Analysis Working Group (Wood and Dublin 2010), showed growth in geothermal electricity production of 10.4 GWe by 2030 for the base supply curve and 14.0 GWe for the target supply curve. To replicate these growth scenarios, geothermal resources were selected beginning with the cheapest LCOE and proceeding to the most expensive LCOE until the total electricity generation equaled the total generation potential for the scenario. Only 50% of the undiscovered resources in a given state were allowed to be included in the scenario due to the uncertainty associated with these resources that was not captured in the supply curve cost estimates. This set of scenarios includes realistic estimates of geothermal growth rates and allows for the identification and analysis of potential near and intermediate term water related challenges.

TABLE 2 Summary of Water Resource Assessment Scenarios

Scenario Category	Specific Scenarios Included
Resource type	Identified hydrothermal, unidentified hydrothermal, near-field EGS
Levelized cost of electricity	Base supply curve – \$0.05, \$0.10, \$0.15, \$0.20/kWh Target supply curve – \$0.05, \$0.10, \$0.15, \$0.20/kWh
NEMS-GPRA 2030	Base supply curve (10.4 GWe), target supply curve (14.0 GWe)

2.6 RESULTS AND ANALYSIS

GIS maps were created to show the geothermal electricity generation and associated water consumption by state for each scenario considered. An example map is shown in Figure 1. The maps are color coded according to water consumption, with darker colors representing greater water consumption. Numerical values for electricity generation capacity and water consumption are provided by state. For resources where exact geographical locations are available (identified hydrothermal and near-field EGS), icons indicate the location if it is expected to be exploited using a binary or flash plant.

A complete set of the maps generated is in Appendix A. Data from these maps are used for the additional analysis discussed below. The geothermal supply curve upon which this analysis is based considers the potential for geothermal resources in the entire United States. However, no significant hydrothermal or near-field EGS resources are identified east of Colorado. Some deep EGS resources do exist in the Eastern U.S. and are included in the supply curve, but at high costs that do not show up in any of the scenarios considered.

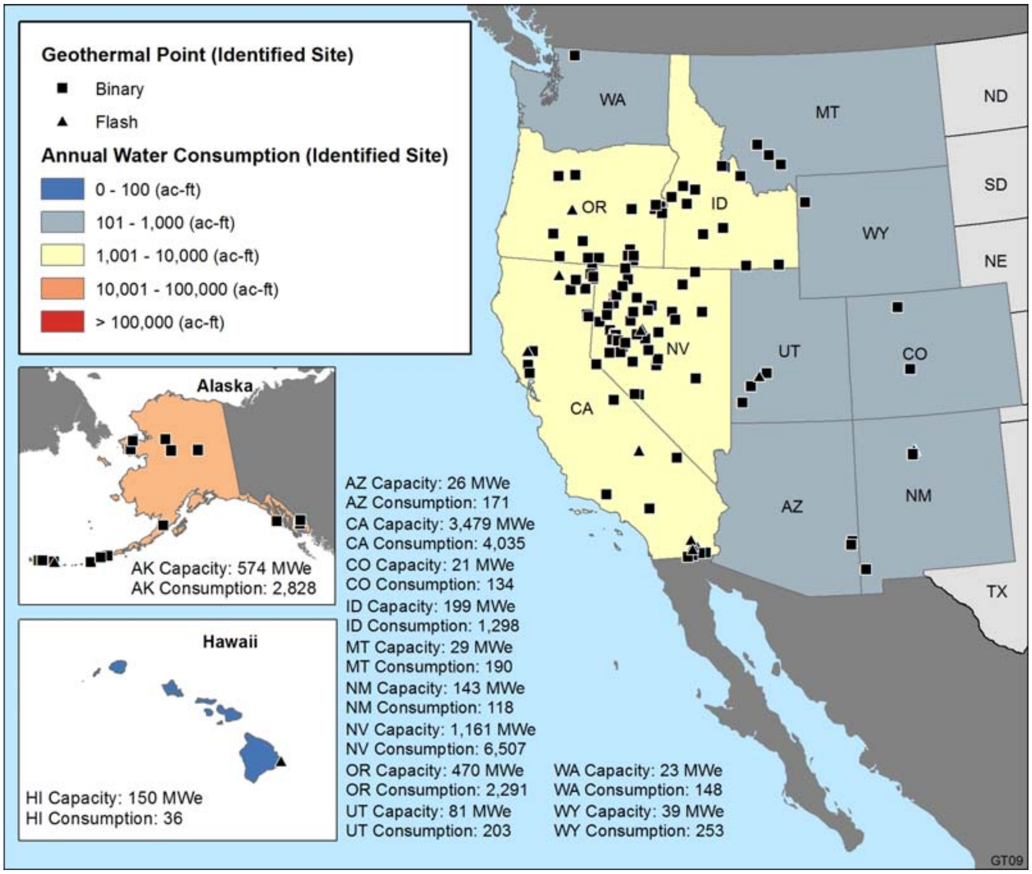

FIGURE 1 Example GIS Map: Geothermal Water Demand, All Identified Hydrothermal Resources.

Data from the resource type scenarios are shown in Figures 2 and 3. Figure 2 summarizes the potential geothermal resources by state and resource type. Figure 3 summarizes the associated water consumption by state and resource type. It is apparent that near-field EGS resources significantly impact the overall water demand. While these resources are a relatively small percentage of the potential generation capacity in most states, they contribute significantly more to the overall water demand. This is not unexpected due to the higher per-kWh water consumption for EGS systems.

California has by far the greatest geothermal potential, with Nevada a distant second. However, examination of each state’s water consumption shows Nevada’s potential geothermal water demand is nearly as high as California’s, despite its having a much smaller resource potential. This can be explained by comparing the identified and unidentified hydrothermal resources in both states. While these resources represent a small portion of the water demand in California, they make up a significantly larger fraction of the overall water demand in Nevada. Geothermal resources in Nevada are generally at lower temperatures than those in California, and, as a result, require more fresh-water-intensive binary systems.

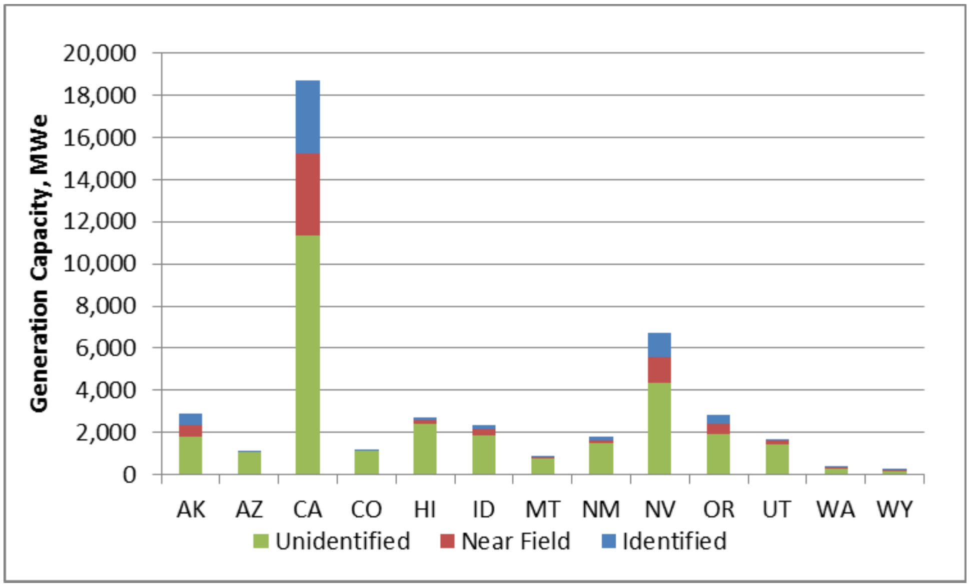

FIGURE 2 Potential Geothermal Electricity Generation Capacity by Resource Type and State.

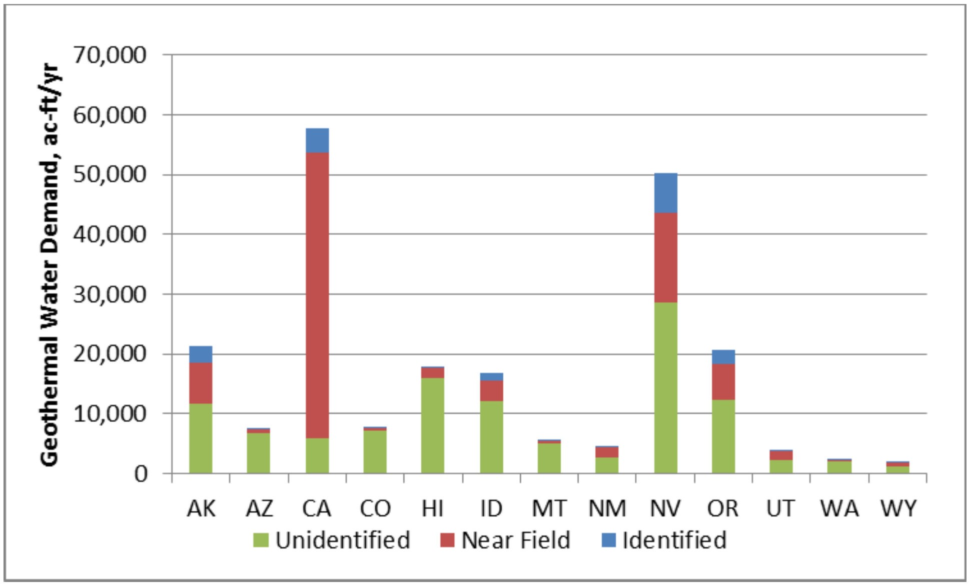

FIGURE 3 Potential Geothermal Water Demand by Resource Type and State.

LCOE scenarios are summarized in Figures 4 and 5. Note that the $0.20 per kWh scenarios, with generation capacities of just under 300,000 MWe for the target case and just over 30,000 MWe for the base case, are not included on the graphs so as not to distort their scales. The order-of-magnitude difference in the two $0.20 per kWh cases is driven by estimated cost reductions for deep EGS resources within the target supply curve. In the base case, all deep EGS resources remain uneconomical until well above $0.20 per kWh.

While the target and base cases show fairly similar resource potential and water consumption below $0.10 per kWh, the cost reductions start to have a significant impact between

$0.10 per kWh and $0.15 per kWh. The increase in resource potential in the target case, however, does not come without a cost. Figures 4 and 5 show that while the potential generation of the target case is twice that of the base case for the $0.15 per kWh scenarios, the water consumption more than quadruples, because most of the incremental increase in supply in the target case is from more water-intensive EGS resources.

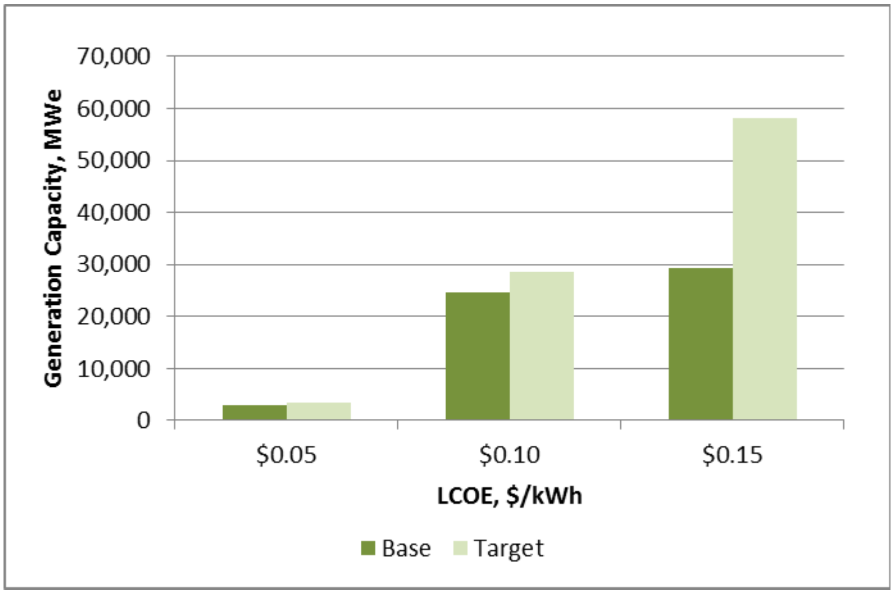

FIGURE 4 Potential Geothermal Electricity Generation Capacity by LCOE.

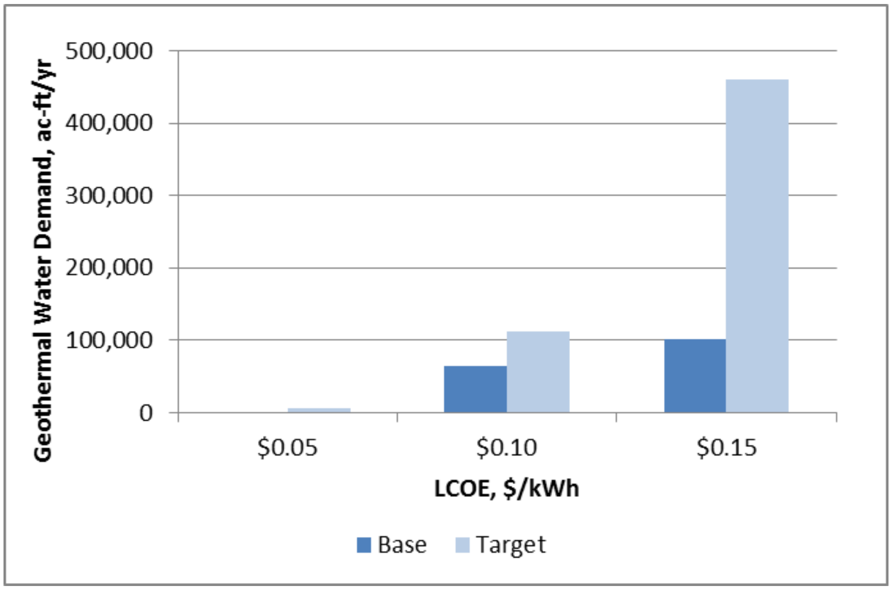

FIGURE 5 Potential Geothermal Water Demand by LCOE.

The final set of scenarios analyzed is based on NEMS modeling results for future geothermal capacity growth by the year 2030. They are intended to represent realistic medium- to long-term growth projections for geothermal capacity additions. The GIS maps for these scenarios are shown in Figures 6 and 7.

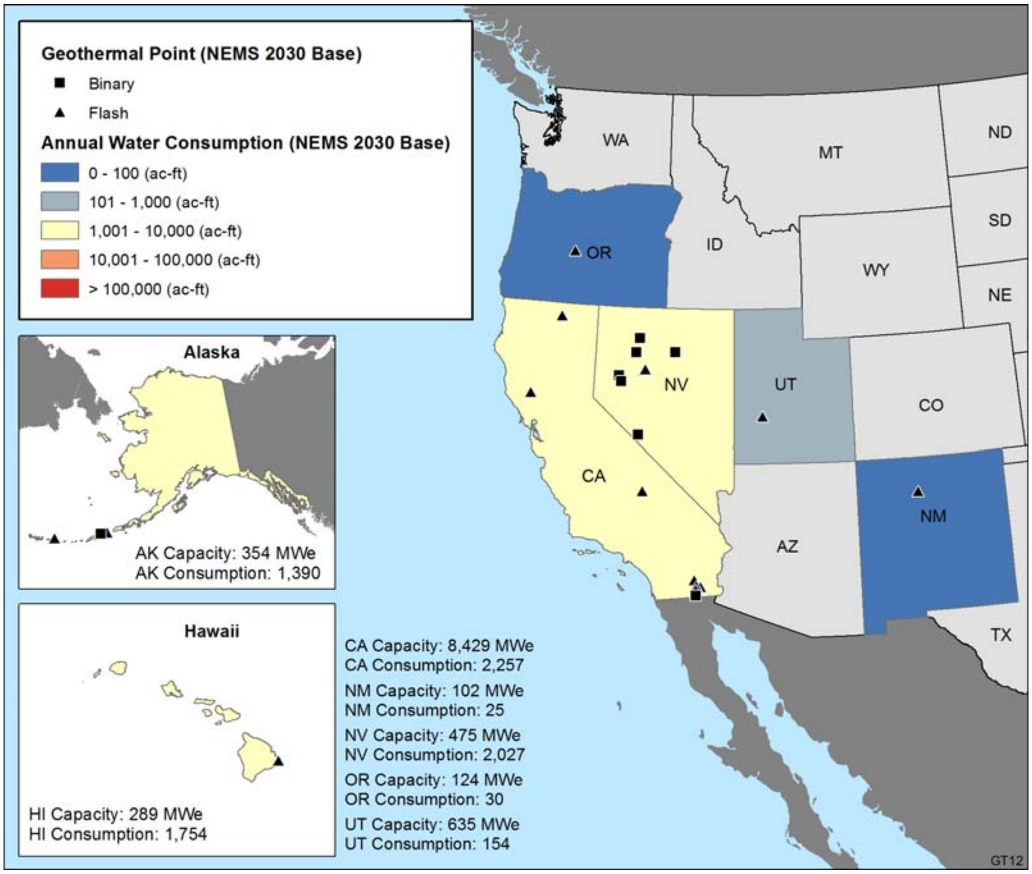

FIGURE 6 Geothermal Generating Capacity Growth, NEMS-GPRA 2030, Base Cost Curve.

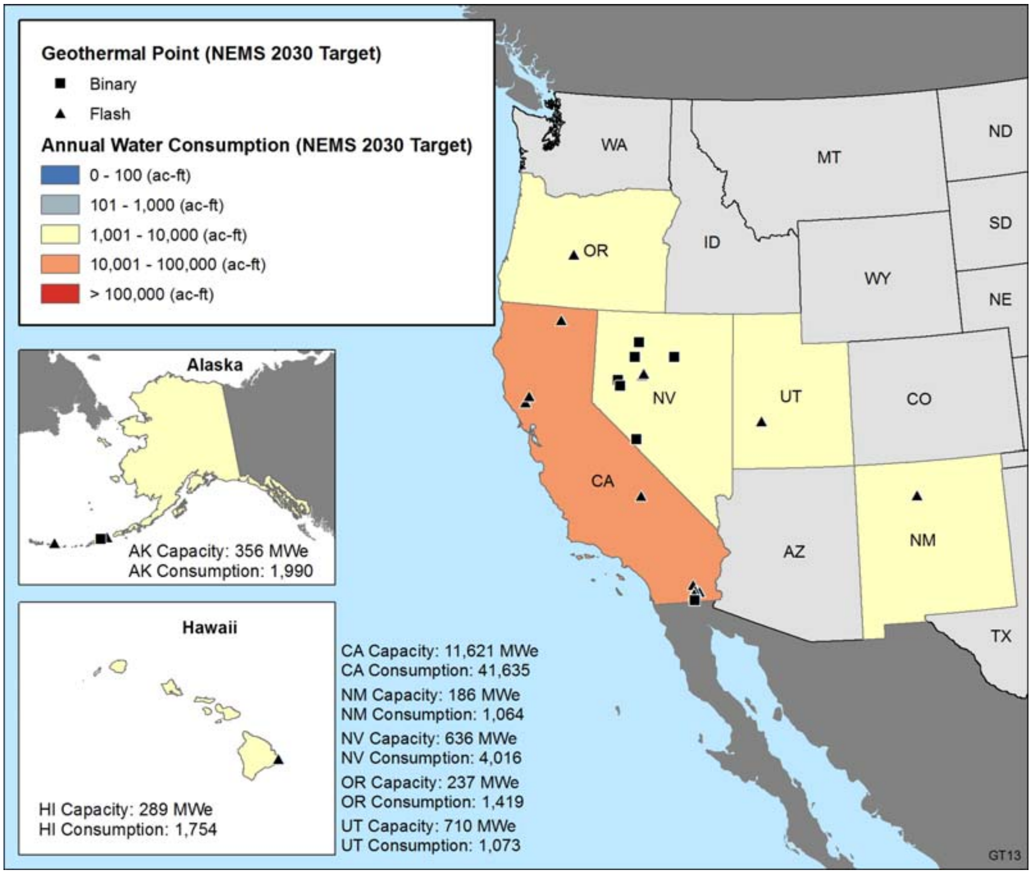

FIGURE 7 Geothermal Generating Capacity Growth, NEMS-GPRA 2030, Target Cost Curve.

The results are further summarized in Figures 8 and 9, breaking out the generation capacity and water consumption by state. In both the base and target cases, growth in geothermal capacity is dominated by California, with more than 80% of the capacity additions by 2030 in both cases. However, there is a stark contrast in the water demand between the base and target cases for California. In the base case, nearly all of the capacity addition is in the form of hydrothermal flash plants, which have minimal freshwater requirements.

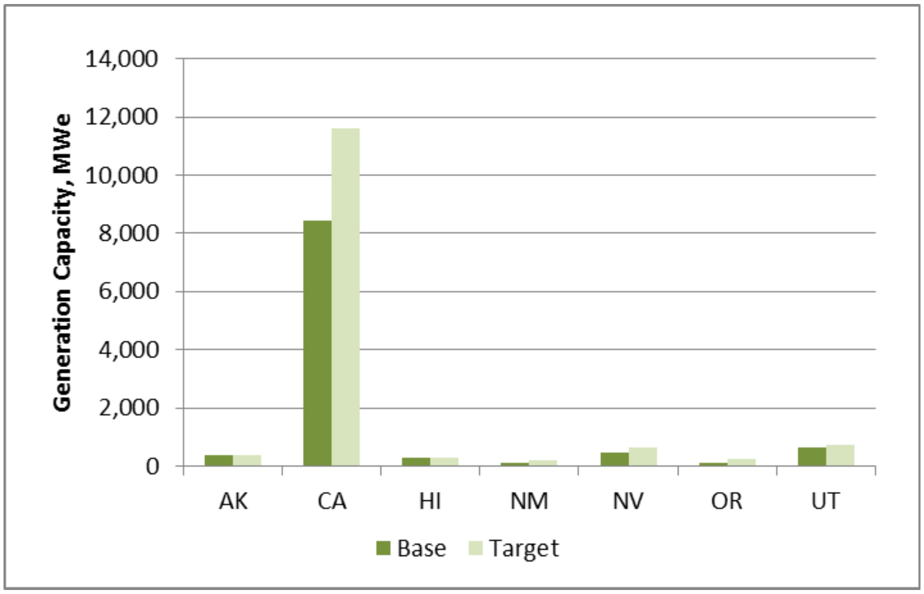

FIGURE 8 NEMS-GPRA 2030, New Geothermal Generation Capacity by State.

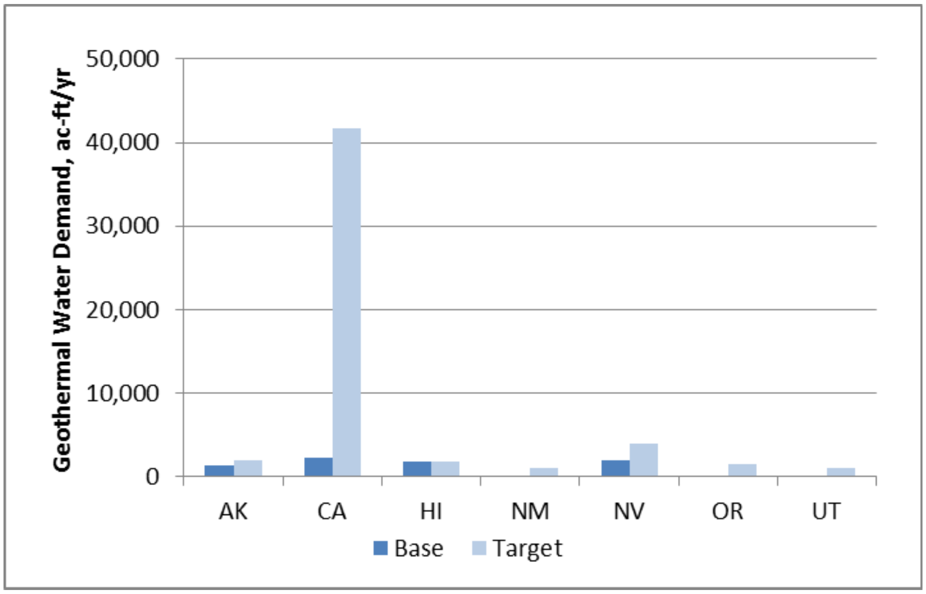

FIGURE 9 NEMS-GPRA 2030, New Geothermal Water Demand by State.

These scenarios were further analyzed within the context of existing electricity and water demand in each state. Both electricity generation and water demand were calculated in terms of percent growth relative to existing baseline data. For electricity generation the baseline was the most recent EIA data on state electricity generation capacity from 2009 (EIA 2011c). For water consumption the baseline was the most recent USGS data on state water withdrawals for recirculating cooling from thermoelectric power production from 2005 (Kenny et al. 2009). The USGS does not track water consumption, only water withdrawals. However, it does separate withdrawals between once through and recirculating cooling systems and fresh and saline water sources. Fresh water withdrawals for recirculating cooling were selected as the most appropriate proxy for water consumption since most water withdrawn for recirculating cooling is eventually lost to evaporation within the cooling system. This assumption underpredicts the total water consumed for thermoelectric power generation as a small fraction of the water withdrawn is also consumed in once through systems. The USGS estimates that the evaporative loss from once through systems is less than 3% of withdrawals (Solley et al. 1998). The error introduced by this factor is expected to be small in the states of interest because fresh water once through cooling systems are not common in these states and the volumes withdrawn are small as shown in Table 3. The energy and water growth results are shown in Figure 10.

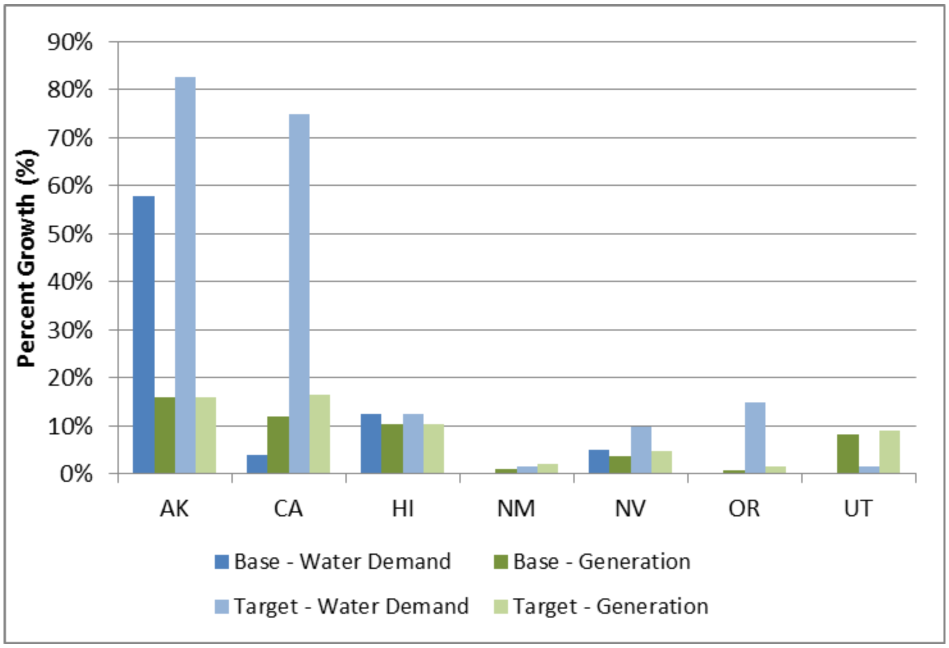

FIGURE 10 NEMS-GPRA 2030, Growth in Electricity Generation and Water Demand from Geothermal as a Percent of Existing Total Electricity Generation and Water Consumption for Thermoelectric Generation by State.

Drawing broad and definitive conclusions from Figure 10 is challenging as the results vary significantly between states and scenarios. In some cases water consumption increases significantly faster than electricity generation, while in other cases the opposite is true. There are two main drivers of this variability in the results. The first factor is the increased water intensity observed in the target scenario as compared to the base scenario resulting from increased market penetration of near-field EGS systems, which has been discussed above. The second factor is the variability in baseline water intensity between states.

According to Figure 10, it appears that growth in geothermal generation in Alaska, California, Nevada, and Oregon may result in significant growth in water consumption for electricity generation in at least one scenario. Details on the baseline water demand for each state are included in Table 3. Looking at the quantities of water currently used for recirculating cooling in each of these states, it appears that they are low relative to some of the other states included, especially in Alaska and Oregon. California is by far the largest energy producer in the study; however, it is only the sixth largest consumer of water for recirculating cooling of the 13 states included in this study. To further examine this issue, the water intensity in gal per kWh was calculated for each state utilizing power generation data from EIA (EIA 2011d). Figure 11 shows the baseline water intensity in each state compared to the average water intensity for the incremental growth in geothermal generation in each scenario assuming the same 90% capacity factor described in section 2.3.

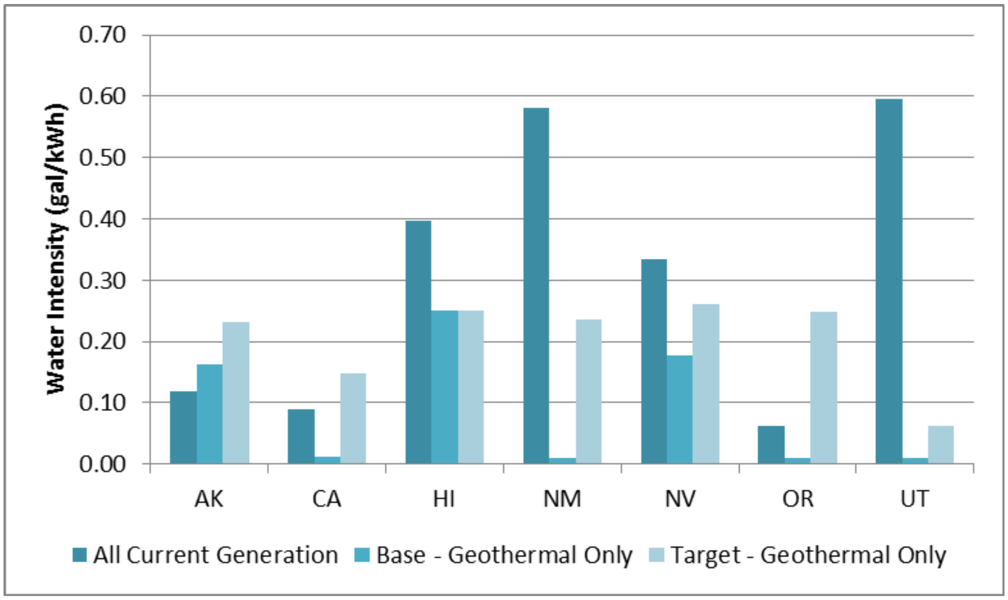

FIGURE 11 NEMS-GPRA 2030, Baseline Water Intensity vs. Incremental Water Intensity from New Geothermal Generation by State.

The results in Figure 11 illustrate the significant variability in the baseline water intensity by state. California and Oregon have the lowest water intensities with values less than 0.1 gal per kWh. California appears to keep its fresh water intensity low through heavy reliance upon once through cooling systems utilizing seawater (Kenny et al. 2009). Oregon has low baseline water consumption due to the significant percentage of its electricity that is generated from hydroelectric power, which does not directly consume water as quantified by the USGS (EIA 2011c). It should be noted that hydroelectric power indirectly consumes water through surface evaporation from reservoirs, although there is some controversy over how to allocate the water consumption considering the multiple economic uses of reservoirs in addition to energy production (e.g., water storage, flood control, recreation).

Looking broadly at the baseline water demand in the states likely to see geothermal growth, we find a trend of low water consumption relative to the rest of the country. While the 13 states included in Table 3 account for 21% of the nation’s electricity generation capacity, they only account for 3% of national water demand for recirculating cooling, and less than 1% of total national water withdrawals for power production (EIA 2011c and Kenny et al. 2009). Furthermore, while nationally, water withdrawals for thermoelectric power account for 49% of total water withdrawals, they account for a far smaller percentage in these states — less than

10% in all states and less than 2% in most states. California, which has both the greatest geothermal potential and potentially one of the highest growth rates in water demand from geothermal, currently uses only 0.15% of its fresh water for power generation.

Low existing water demand for electricity generation is an indicator of existing water related stress, and highlights the potential for challenges with increasing water demand for any new electricity generation in these states. Unfortunately geothermal power will not be immune from these challenges and conflicts. Understanding the potential water demand for energy generation and the existing water constraints facing these states will be essential to future energy planning.

Identifying alternative sources of nonpotable water represents one opportunity to reduce operational water consumption from geothermal systems and helps mitigate water-related risk to the growth of the industry. Table 3 includes recent estimates of total annual volumes of produced water from oil and gas activities in each state. In seven of the 13 states, the volume of produced water exceeds the total potential water demand from geothermal in the state (excluding deep EGS resources) shown in Figure 3 by a factor of four. The viability of using produced water for operational make-up water for geothermal is untested and will depend upon both the distance between geothermal fields and oil and gas plays within each state and the geochemical compatibility of the waste brine with the geothermal formation.

TABLE 3 Current Water Withdrawals for Electricity and Availability of Produced Water

State	2005 Fresh Water Withdrawals for Recirculating Cooling (ac-ft/yr)	2005 Fresh Water Withdrawals for Once-Through Cooling (ac-ft/yr)	Percent of Total Fresh Water Withdrawals for Energy	Total Oil and Gas Produced Water (ac-ft/yr)
AK	2,409	35,178	3.83%	103,260
AZ	95,003	5,747	1.44%	9
CA	55,568	0	0.15%	328,987
CO	58,257	79,767	0.91%	49,503
HI	14,004	28,344	8.46%	0
ID	1,232	0	0.01%	0
MT	32,265	68,452	0.89%	23,462
NM	62,626	0	1.68%	85,856
NV	41,228	0	1.55%	877
OR	9,467	0	0.12%	0
UT	69,684	0	1.29%	19,208
WA	33,834	476,136	8.13%	0
WY	68,227	181,492	5.05%	303,591
Total US	142,300,000	17,700,000	49%	2,700,000

Sources: Kenny et al. 2009 and Clark and Veil 2009.

3 PART II: WATER USE IN GEOPRESSURED GEOTHERMAL SYSTEMS

3.1 INTRODUCTION

Geopressured geothermal power plants take advantage of underground pressurized reservoirs that contain both hot water and dissolved natural gas. The resource base includes thermal energy, mechanical energy, and chemical energy (methane). Because the potentially recoverable mechanical energy is less than 1% of both the thermal and chemical energy (Papadopulos et al. 1975), energy production from this resource has focused on thermal and chemical energy (Wallace et al. 1979; Randolph et al. 1992). The first hybrid geopressured geothermal power plant in the U.S., Pleasant Bayou in Brazoria County, Texas, generated electricity from the geofluid and separated the natural gas to test both producing electricity from combustion in an on-site hybrid power plant and processing the natural gas to direct-to-sales pipelines (DOE 2010; Randolph et al. 1992). Both scenarios are evaluated. The dissolved gas and any free gas are separated from the geofluid prior to directing the geofluid through a binary system. The gas is then directed to a gas engine for direct electricity generation or to a gas pipeline, and the geofluid is directed to an injection well that is not hydraulically connected to the geopressured reservoir. Figure 12 shows the locations of geopressured geothermal resources in the United States.

FIGURE 12 Geopressured Geothermal Resources in the U.S. (DOE 2010).

3.2 PURPOSE

Argonne carried out a life-cycle analysis (LCA), reported in a companion document (Sullivan et al. 2011), to quantify energy and environmental benefits of geopressured geothermal systems by examining proximity to infrastructure, resource availability, and tradeoffs associated with well depth and resource temperature. This report summarizes the LCA as it pertains to water use in geopressured power plants.

3.3 APPROACH AND METHODS

This section details the approach and methods for the water LCA for geopressured systems. The analysis builds upon methods developed in a recent analysis of water consumption for geothermal electricity production to estimate the water requirements for geopressured systems (Clark et al. 2011). It also relies on life-cycle inventory data generated for a parallel effort looking at quantifying the energy and environmental benefit of these systems (Sullivan et al. 2010).

3.3.1 Life Cycle Analysis

In assessments of water use at power plants, two water quantities are commonly listed: water withdrawn and water consumed. The former is defined as water taken from ground or surface water sources mostly used for heat exchangers and cooling water makeup, whereas the latter is water either consumed in the combustion process (e.g., in coal and biomass gasification plants — not covered here) or evaporated and hence no longer available for use in the area where it was withdrawn. Water consumption also includes water withdrawals related to construction stage activities (e.g., in drilling muds and cement) in this analysis. The objective is to account for the consumed water — withdrawn water that does not get returned to its area of extraction in liquid form. The system boundary does not account for water required in the off-site manufacturing of steel or other materials, for geofluid from the reservoir that may be lost but is not replaced, nor for geofluid produced from a geopressured reservoir that is injected into another reservoir.

3.3.2 Well Field Development

This section describes the assumptions and methodologies used to represent the well field for our scenarios. Table 4 shows the scenarios across several design parameters, which affect performance, cost, and environmental impacts. The scenarios were modeled in the U.S. Department of Energy’s Geothermal Electricity Technology Evaluation Model (GETEM), and the simulation was run multiple times in GETEM to create a range of possible outcomes (DOE 2011).

TABLE 4 Parameters Evaluated in Geopressured Geothermal Scenario

Parameters	Assumed Values
Producer/injector ratio	2:1
Number of turbines	1
Generator type	Binary
Cooling	Air-cooled
Temperature, °C	130–150
Thermal drawdown, % per year	0
Well replacement	None
Production well depth, km	4–6
Injection well depth, km	2–3
Gas/brine ratio (SCF/STB*)	25–35
Flow rate, kg/s	35–55
Distance between wells, m	1,000
Location of plant to wells	Central

* SCF/STB = standard cubic feet per stock tank barrel.

The parameters were developed according to input from industry experts and well field characteristics at Pleasant Bayou and other geopressured geothermal test wells, then incorporated into GETEM (Randolph 1992, DOE 2010, Luchini 2011). Because GETEM assumes air cooling for binary systems, air cooling was also assumed for this analysis, although it is recognized this assumption may result in lower sales and higher LCOE in warmer climates than might be realized with water cooling. To model the well field, it was assumed that the production wells would be twice the length of the injection wells according to well configurations at Pleasant Bayou (Randolph et al. 1992). The production and disposal wells are assumed to be not hydrologically connected; the spent geofluid leaving the plant is assumed to be directed to a disposal well. The components included in the inventory for each well are depicted in Figures 12 and 13.

The drilling phase of the geopressured geothermal power plant life cycle requires heavy equipment, such as drill rigs, fuel, materials, and water. The material inventory and fuel requirements for constructing the well field are detailed in a companion report, Sullivan et al. (2011), and details of the well designs are provided in Appendix B.

During drilling, fluids or muds lubricate and cool the drill bit to maintain downhole hydrostatic pressure and to convey drill cuttings from the bottom of the hole to the surface. Drilling muds contain chemicals and constituents to control such factors as density and viscosity and to reduce fluid loss to the formation. The total volume of drilling muds depends on the volume of the borehole and the physical and chemical properties of the formation. As a result, mud volumes vary, and predicting the volume for a typical drilling project can be challenging.

The same approach as outlined in Clark et al. (2011) was used to estimate fluid volume. For the purposes of this study, average mud volume data were obtained from the literature (EPA 1993; Mansure 2010), and the ratio of barrels of drilling mud to barrels of annular void was found to be 5:1.

The reworked well designs described in Randolph et al. (1992), were specified according to two different methods. The production well was specified according to grade and thickness rather than grade and weight per foot, which is customary per American Petroleum Institute. The injection well was specified according to grade and weigh per foot. These dimensions were used to determine the total material inventory for both well designs at the various depths.

In addition to use as a drilling fluid, water is also used to cement well casing. To determine the volume of water used for cementing, the volume of cement was calculated. This was done for each well by calculating the total volume of the well and the volume of the casing and interior, and accounting for excess cement for each casing interval. Class H cement was assumed for the Pleasant Bayou geopressured well (Randolph et al, 1992). Class H cement is used in most locations including the Gulf Coast while Class G cement is primarily used in California, the Rocky Mountains, and Alaska. Because geopressured geothermal resources exist in various geographic regions of the U.S., including the Gulf Coast and California (DOE 2010), calculations were conducted with both Classes G and H cement. Class G requires more water than Class H as shown by the corresponding estimated water (gal/sack) and slurry volumes (cu ft/sack; see Table 5). Classes G and H cement with no silica flour were assumed for the conductor pipe and surface casing, while Classes G and H with 40% silica flour were assumed for the rest of the casing cement because silica flour enhances cements for high-temperature applications (Bourgoyne 1991).

TABLE 5 A Comparison of Class G and Class H Cement

Parameter	Class G		Class H	
Silica flour (%)	0	40	0	40
Water (gal/sack)	5	6.8	4.3	5.99
Slurry volume (cu ft/sack)	1.15	1.62	1.06	1.51

Sources: Halliburton (2006) and Bourgoyne et al. (1991).

3.3.3 Pipeline Construction

Pipelines are required to carry geofluid to and from the power plant. For this study, it is assumed that each of two production wells has a separate pipeline to deliver the geofluid to the power plant, a separate pipeline with associated material usage calculated as part of the plant infrastructure, and a final pipeline to carry the geofluid to the injection well from the power plant. This study assumes two production wells and one injection well per geothermal power plant. Because the pipelines are aboveground, they require support structure. The two production well pipelines and the one injection well pipeline have associated steel, water, cement, and diesel uses as well. The portion of the pipeline that is relevant to water use is the concrete structural support. The spacing of the supports is determined by pipe diameter, which must be optimized according to the desired flow rate. We determined that the pipelines from the production wells to the plant would have a diameter of 8 inches, while the diameter of the pipe from the plant to the injection well would be 10 inches (Sullivan et al. 2010). Given the diameter of each hole (15.75 inches) and the depth (6 ft), one can calculate the volume of the hole. The volume of concrete required is the hole volume minus the volume taken up by the 12-inch-long, 0.5-inch-diameter rebar. The recipe assumed for this analysis is for controlled low-strength material concrete and assumes 125 pounds of Portland cement, 2,500 pounds of fine aggregate, and 35–50 gallons of water (IDOT 2007).

3.3.4 Power Plant Construction

Water volumes for plant construction were limited to on-site use for concrete. A typical concrete recipe requires approximately 200 g/L of water/concrete (Kendall 2007). To determine the total amount of concrete, results were generated using the Icarus Process Evaluator for a binary geothermal power plant as described in Sullivan et al. (2010). The material and water estimates for the concrete for each scenario are summarized in Table 6.

TABLE 6 Material and Water Requirements for Concrete in Geopressured Geothermal Power Plant Construction

Materials (unit)	Geopressured 2.8 MW	Geopressured 3.6 MW	Geopressured 4.3 MW
Cement (MT)	269	346	414
Gravel (MT)	533	685	818
Sand (MT)	372	478	571
Water (gal)	114	146	175

3.3.5 Operations

With the exception of Pleasant Bayou, there is a lack of experience operating geopressured plants in the U.S. and a lack of data on operational water consumption. In addition to electricity generation, geothermal power plants may use freshwater to condense vapor for (1) reinjection in the case of the geofluid for flash systems, (2) reuse of the working fluid in binary systems, and (3) maintaining reservoir pressure for long-term sustainability. Freshwater may also be used in normal operations to manage dissolved solids and minimize scaling. The geopressured geothermal power plant evaluated in this study is air-cooled, and the spent geofluid is directed to a separate disposal well that does not maintain reservoir pressure. Freshwater consumption should be minimal in this phase.

The additional operations of the gas-handling facilities for geopressured geothermal systems result in geofluid loss when water is diverted in the initial separation process. That fluid is “lost” to gas processing; however, unlike traditional binary systems where freshwater would be added to make up for any operational losses to maintain reservoir pressure, it is not necessary to replace the lost geofluid for geopressured geothermal systems.

3.4 RESULTS OF THE LIFE CYCLE ANALYSIS

Water use was quantified at each stage of the life cycle and aggregated to compare with other geothermal power systems. The exploration stage was not considered.

3.4.1 Construction

For geopressured geothermal, we considered the freshwater requirement throughout the life cycle. Figure 13 depicts the water required to construct wells at various depths, accounting for the water used in drilling fluid and in the cementing of casing. The difference in the trend between shallow and deep wells in the figure is due to the difference in well design between the injection and production wells.

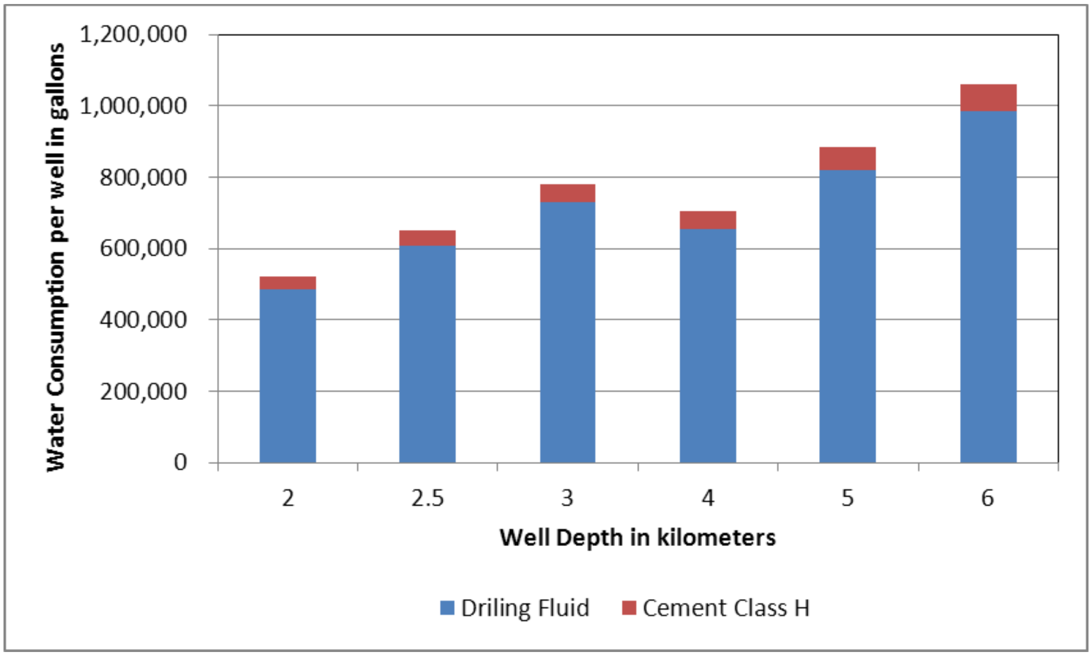

FIGURE 13 **Volume of Water Consumed in Drilling and Constructing Geopressured Geothermal Wells according to Depth of Injection Well (2, 2.5, and 3 km) and Production Well (4, 5, and 6 km), Based on Designs Used at Pleasant Bayou (Randolph et al. 1992).**

Figure 13 also assumes that Class H cement is used. As described in the Approach and Methods section, Class H uses less water than Class G cement. However, when comparing wells cemented with Class H to Class G, the difference in cement choice only affects the water consumption per well by 0.4%.

The water consumption for all construction associated activities including pipeline and power plant construction is presented in Table 7. As Table 7 shows, the drilling fluids consume the largest volume of water during the construction stage. Again the majority of the water consumption occurs during drilling, with the pipeline construction and power plant construction consuming only 0.1–0.2% (pipeline) and 0.01% (power plant) of total water associated with construction activities.

TABLE 7 **Volume of Water Consumed During Geopressured Geothermal 3.6-MW Power Plant and Well Field Construction**

Production Well Depth (km)	Drilling Fluids (gal)	Cement (Class H) for Well (gal)	Concrete for Pipeline (gal)	Concrete for 3.6-MW Power Plant (gal)
4	1,797,935	141,415	3,713	145
5	2,247,419	176,212	3,713	145
6	2,696,903	211,473	3,713	145

The total volume of water required is primarily dependent on well depth. When comparing the construction stage of geopressured geothermal wells to other geothermal systems, it is important to compare according to depth. As Figure 14 demonstrates, geopressured geothermal wells have similar water consumption requirements as other geothermal wells. With the deeper wells, geopressured geothermal wells consistently use less water than EGS wells. While this is likely in part due to the additional water demand of hydraulic stimulation for the EGS wells, the dramatic difference in water demand between the two EGS well designs suggests that well design may be the larger driver in water consumption for the construction stage. The difference in the two EGS well designs used in Sullivan et al. (2010) is due to the number of liners assumed. For the deeper EGS wells, the more robust design assumed one additional liner — for a total of three for the 6-km well and two for the 5-km well. The additional liner resulted in larger-diameter holes, requiring more drilling fluid and more cement to drill and complete the well.

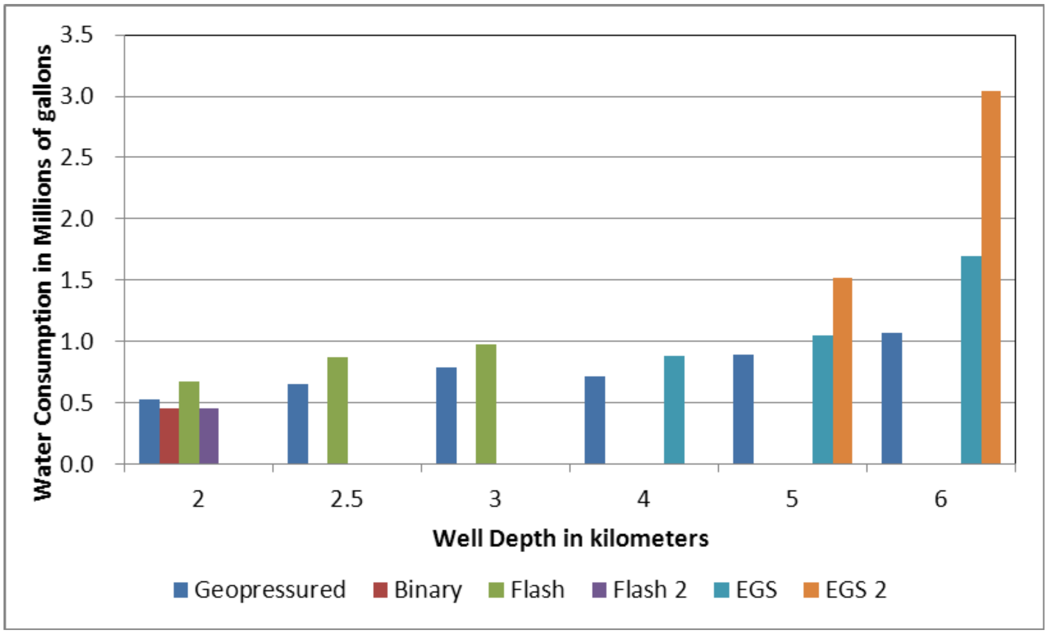

FIGURE 14 Volume of Water Consumed in Drilling and Constructing a Geothermal Well. (Note that both EGS designs include well stimulation.)

3.4.2 Plant Operations and the Life Cycle

The naturally occurring high pressures of geopressured reservoirs make geofluid reinjection into the same reservoir impractical. As a result, makeup water is not needed for recirculation to account for reservoir losses. While this will ultimately impact the long-term sustainability of the reservoir, it significantly reduces water consumption.

Although geofluid is lost during the separation and processing of the natural gas — it is not sent through the heat exchangers of the binary system with the rest of the geofluid — no freshwater is consumed to make up for those losses because the geofluid is directed to a disposal well after use.

While the consumption of freshwater is a concern for other geothermal systems, managing the geofluid is the larger water issue for geopressured operations. The power plant design assumed for this study requires the presence of a suitable formation for a Class II injection well (40 CFR 144.28) to manage the total flow rate produced from the geopressured geothermal resource. The total flow rate of geofluid through the plant depends on the flow rate produced from each well and the total number of production wells. Because these systems are typically at lower temperatures than conventional geothermal systems or EGS, the production volumes per MWe are considerably higher, as shown in Table 8.

TABLE 8 Typical Flow Rates for Four Geothermal Technologies

Geothermal Technology	Daily Flow Rate (kg/day/MWe)
Geopressured	2,160,000–2,210,000
Binary[*]	1,488,000–1,939,000
EGS[+]	1,242,000–1,627,000
Flash[*]	353,000–648,000

[*] Flow rates based on annual production data (CA DOGGR 2009).
[+] Flow rates from Sullivan et al. (2010) and Clark et al. (2011).

Our analysis assumes that all spent geofluid is managed by injection into disposal wells. With a throughput of 23.7 gal per kWh and minimal operational losses, opportunities may exist for water reuse, depending upon the location of the geopressured geothermal system. Figure 11 shows there are geopressured resources in many areas of the continental U.S. and Alaska. Many of these areas are near oil and gas plays where geofluid could potentially be used for enhanced oil recovery or for hydraulic fracturing of shale plays. Additionally, geopressured geothermal resources in the western portion of the U.S. potentially could provide makeup water to other geothermal systems, which consume between 0.01 and 0.72 gal per kWh during operations depending on operating temperature, cooling system (air-cooled or water-cooled), and maintenance of reservoir pressure.

Table 9 compares geopressured geothermal systems with other geothermal systems. The geopressured results are allocated according to geothermal electric power generation (3.6 MW) and natural gas thermal power generation (17.4 MW) because both are produced from the system. This allocation results in water consumption of 4E-04 – 5E-04 gal per kWh lifetime energy output for the geothermal system. If all of the water consumption in plant construction were allocated to the geothermal electric system, the water consumption would be larger, at 0.002–0.003 gal per kWh lifetime energy output, than the hydrothermal systems due to the lower geothermal power generation potential of the cooler geopressured geothermal resource.

TABLE 9 Water Consumption Where Significant for Geothermal Power Generation at Indicated Life Cycle Stages — in gal/kWh of Lifetime Energy Output

Life-Cycle Stage	Cooling System Type		Other	Reference
	Once-through	Cooling towers		
Geothermal – Geopressured				
Plant construction			4E-04 – 5E-04	Argonne[*]
Geothermal – EGS				
Plant construction			0.01	Clark et al. (2011)
Plant construction			0.29	Frick et al. (2010)
Plant operation			0.29 – 0.72	Clark et al. (2011)
Plant operation		0.08		Frick et al. (2010)
Geothermal – Binary				
Plant construction			0.001	Clark et al. (2011)
Plant operation			0.27	Clark et al. (2011)
Plant operation	0.15			Adee & Moore (2010)
Geothermal – Flash				
Plant construction			0.001	Clark et al. (2011)
Plant operation			0.005	Clark et al. (2011)
Plant operation		0.01		Adee & Moore (2010)

[*] Results are from the present report.

Figure 15 compares water consumption for geothermal systems with water consumption values from the literature for a range of other electric power generation technologies as compiled by Clark et al. (2011) and Wu and Peng (2011). A further summary of the literature values can be found in Appendix B. In general, geothermal technologies are on the low end of the water consumption spectrum, as illustrated here. Hydrothermal flash, air-cooled geopressured systems, and wind energy have the lowest average overall water consumption of the electric power technologies.

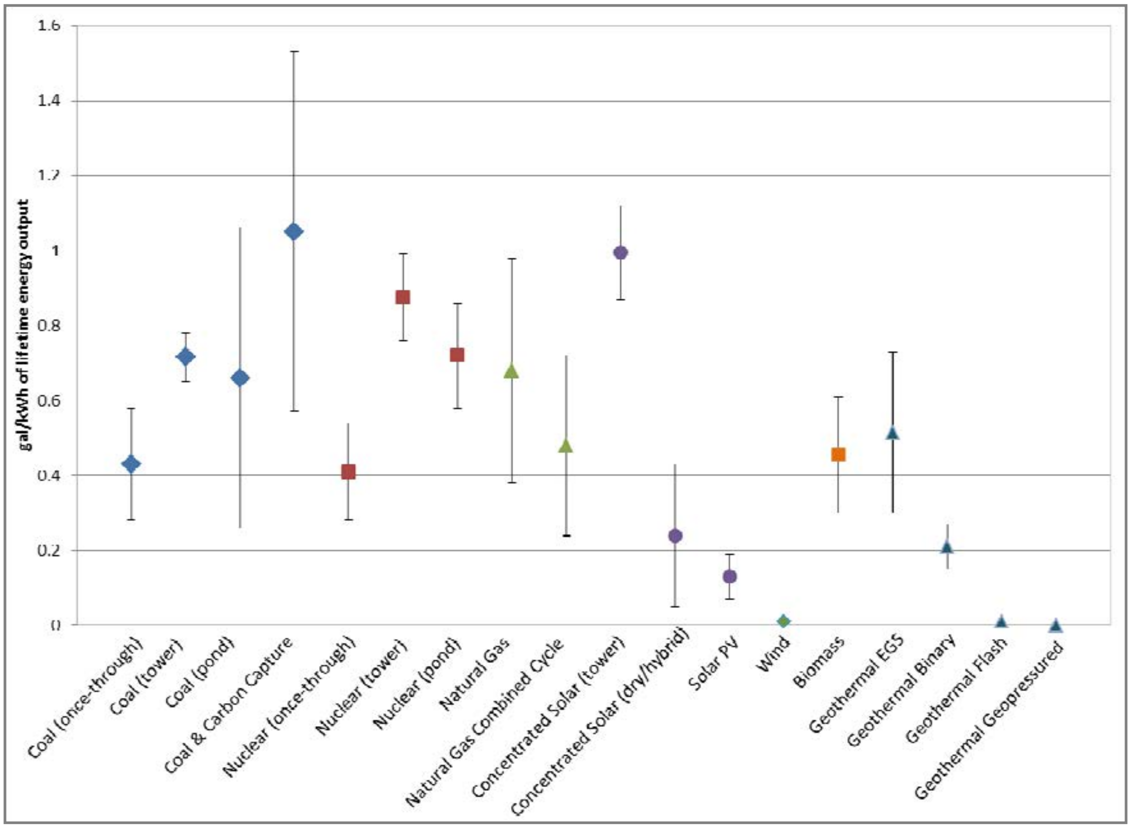

FIGURE 15 Summary of Water Consumption for Electric Power Generation.

4 SUMMARY AND IMPLICATIONS

The results from the two analyses indicate that water management can be an issue in the long-term planning of geothermal power plants. In Part I the growth in water demand resulting from growth in geothermal electricity generation was quantified for a range of scenarios. Analysis of future electricity growth scenarios indicates that in some cases growth in geothermal power will decrease the average water intensity of electricity generation. However in many western states fresh water intensity of electricity generation is already quite low, so growth in geothermal power will result in an increase in water intensity. The availability of produced water from oil and gas was considered as an alternative water source and sufficient quantities are available in several states to support geothermal development.

Geothermal resources are typically located in water-stressed areas, and any increase in water demand in these areas can represent challenges. It is therefore important to examine water consumption within the life cycle to better understand how it can be minimized. To that end, Part II expanded the suite of geothermal technologies evaluated over the life cycle to include low-temperature geopressured geothermal resources.

For geopressured geothermal systems, water consumption is focused on the construction stage, because water for reservoir makeup is not anticipated for these systems. Additionally, when normalized per kilowatt hour of lifetime energy output, water consumption during the construction stage for geopressured geothermal systems is similar to that of hydrothermal systems. Operational water losses are minimal because the spent geofluid is directed to a disposal well, and operators are not concerned with maintaining reservoir pressure for long-term sustainability. Hydrothermal and EGS systems, on the other hand, have the largest volume of water consumption for makeup water during operations. Nonpotable water resources may be available to meet this operational water demand. In addition to potentially reusing geofluid from geopressured geothermal resources, other sources include water produced from oil and gas activities, water extracted from carbon capture and sequestration projects, and saline groundwater resources.

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APPENDIX A – GIS MAPS

This appendix contains the detailed GIS maps generated for the water resources assessment. It contains a total of 13 GIS maps covering the scenarios discussed in the body text. Three main categories of scenarios are represented. Figures A1–A3 show geothermal generation potential and water consumption by resource type. Figures A4–A11 give the geothermal generation potential and water consumption by LCOE. Figures A12 and A13 depict geothermal generation growth and water consumption based on results from the NEMS-GPRA model for the year 2030.

The maps are color coded for water consumption. Numerical values for electricity generation capacity and water consumption are provided by state. For resources where exact geographical locations were available (identified hydrothermal and near-field EGS), these resources are identified by icons indicating the location of each and whether it is expected to be exploited using a binary or flash plant.

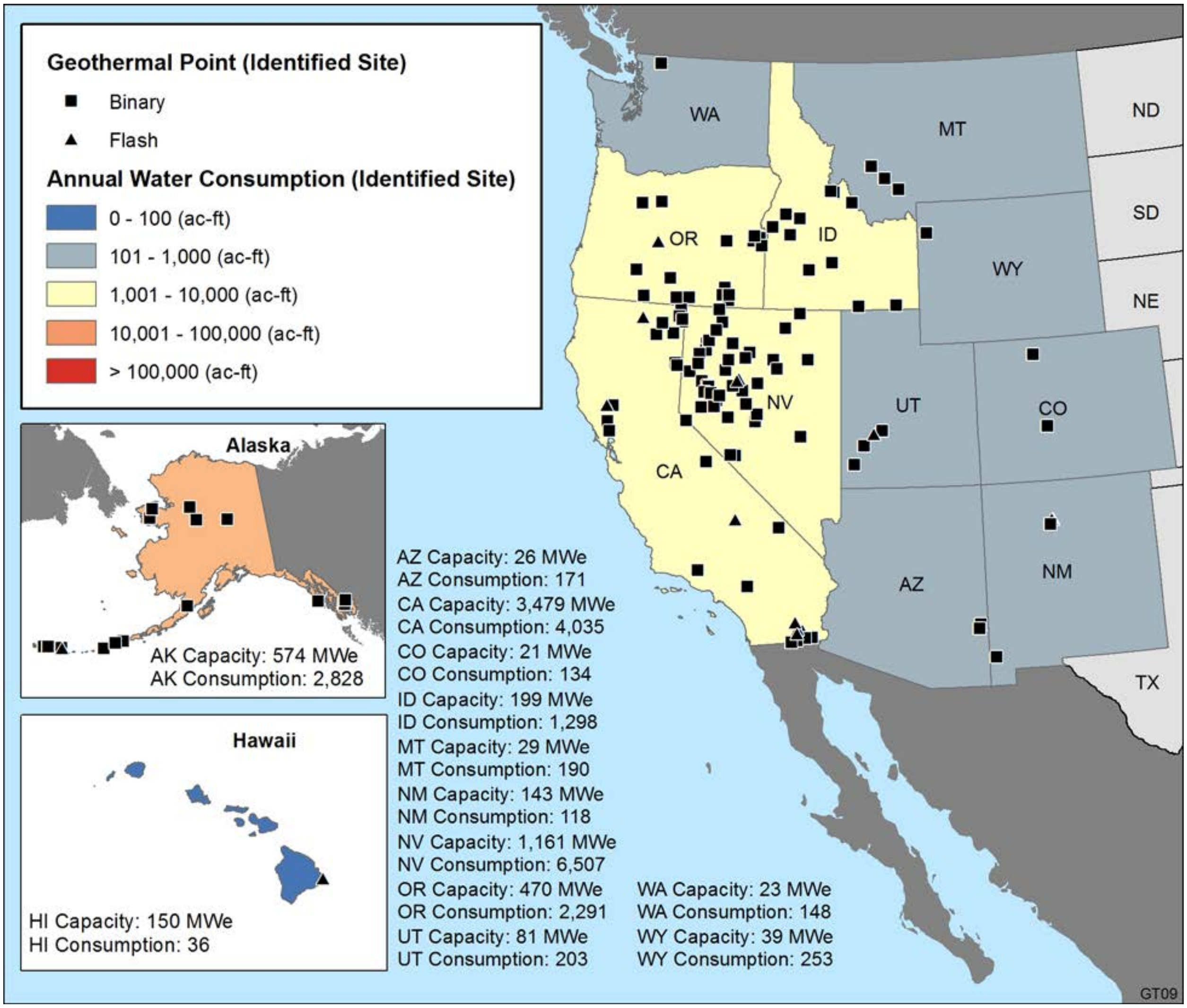

FIGURE A1 Identified Hydrothermal Resources.

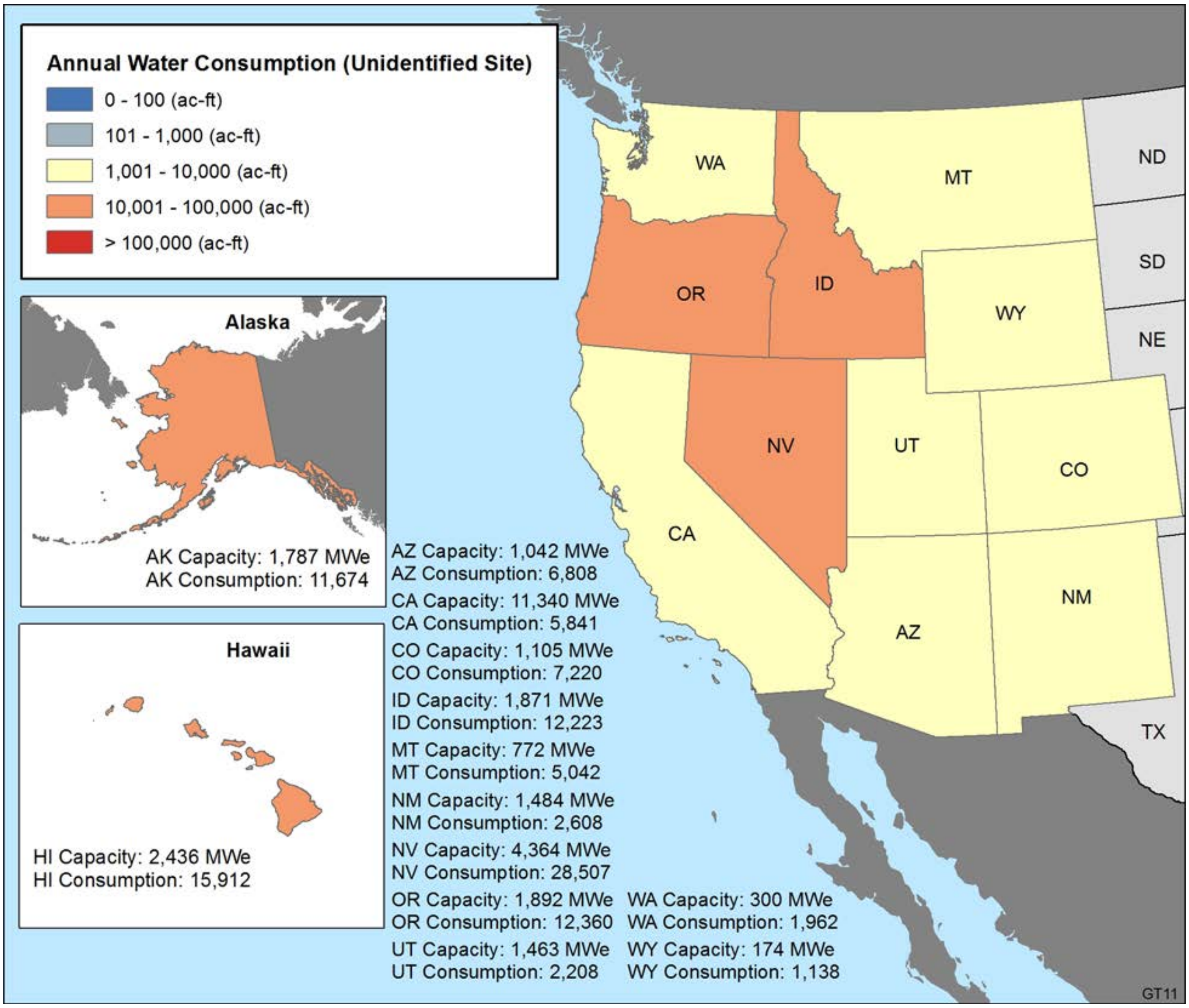

FIGURE A2 Unidentified Hydrothermal Resources.

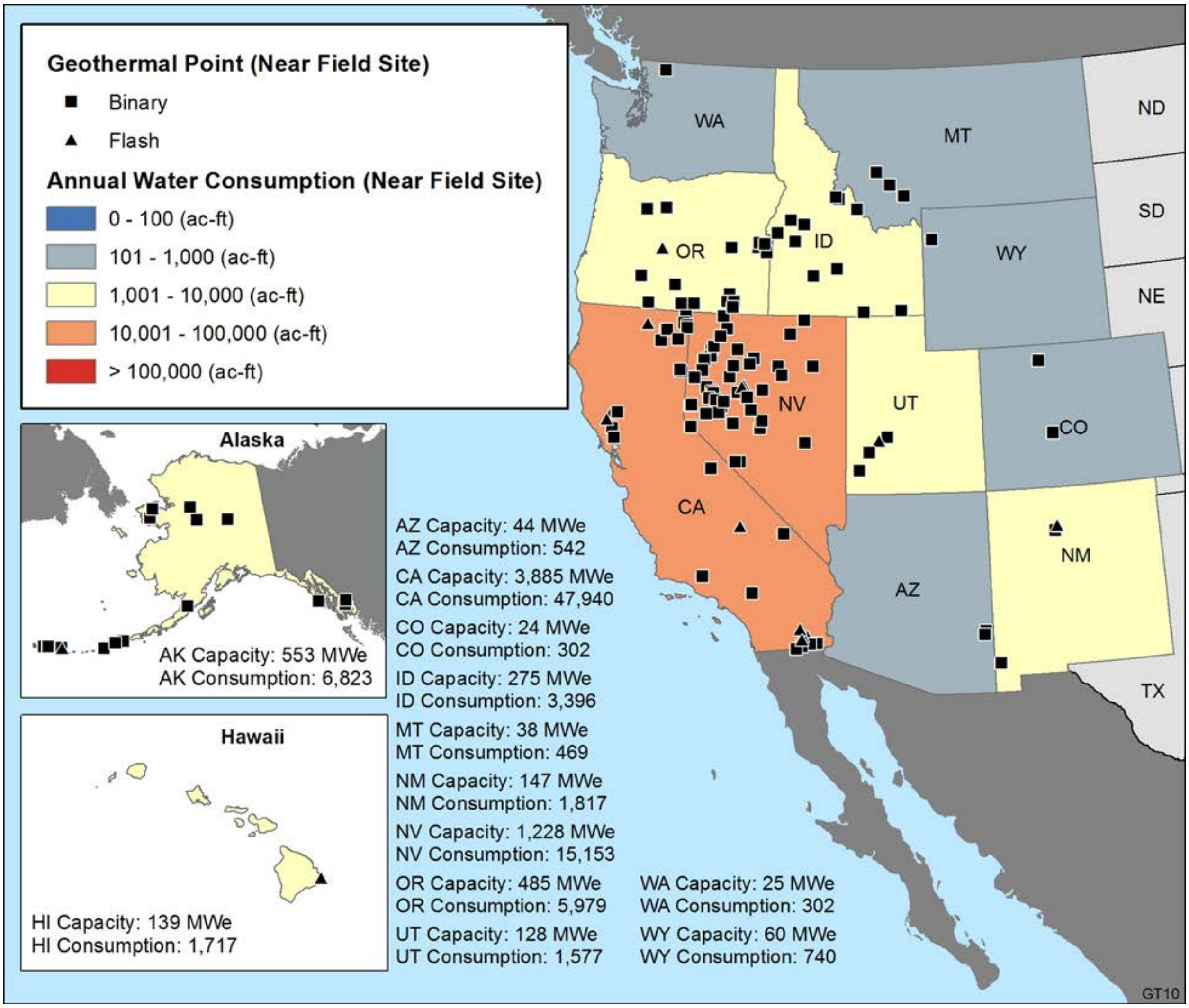

FIGURE A3 Near-field EGS Resources.

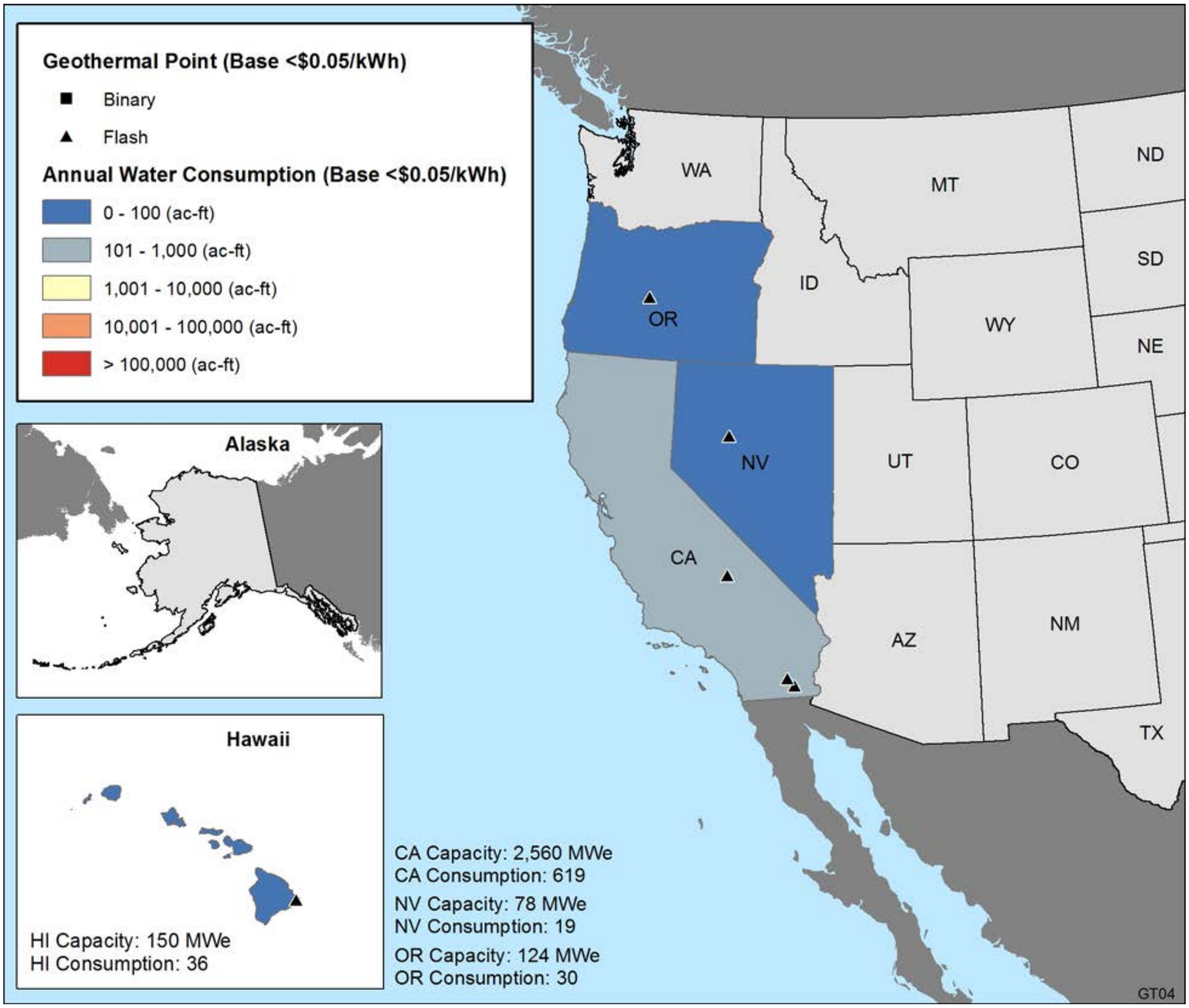

FIGURE A4 Geothermal Resources with LCOE < $0.05/kWh, Base Cost Curve.

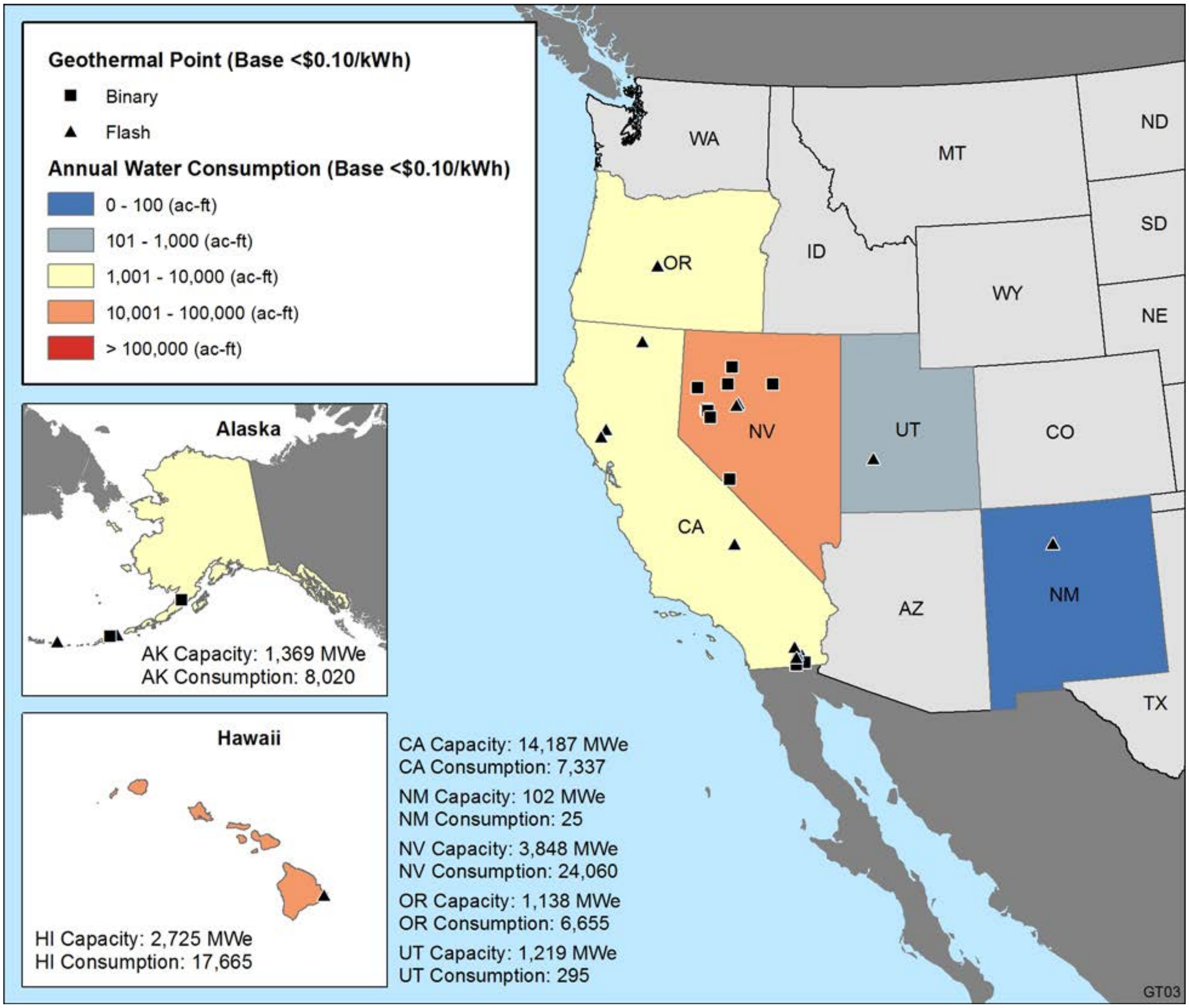

FIGURE A5 Geothermal Resources with LCOE < $0.10/kWh, Base Cost Curve.

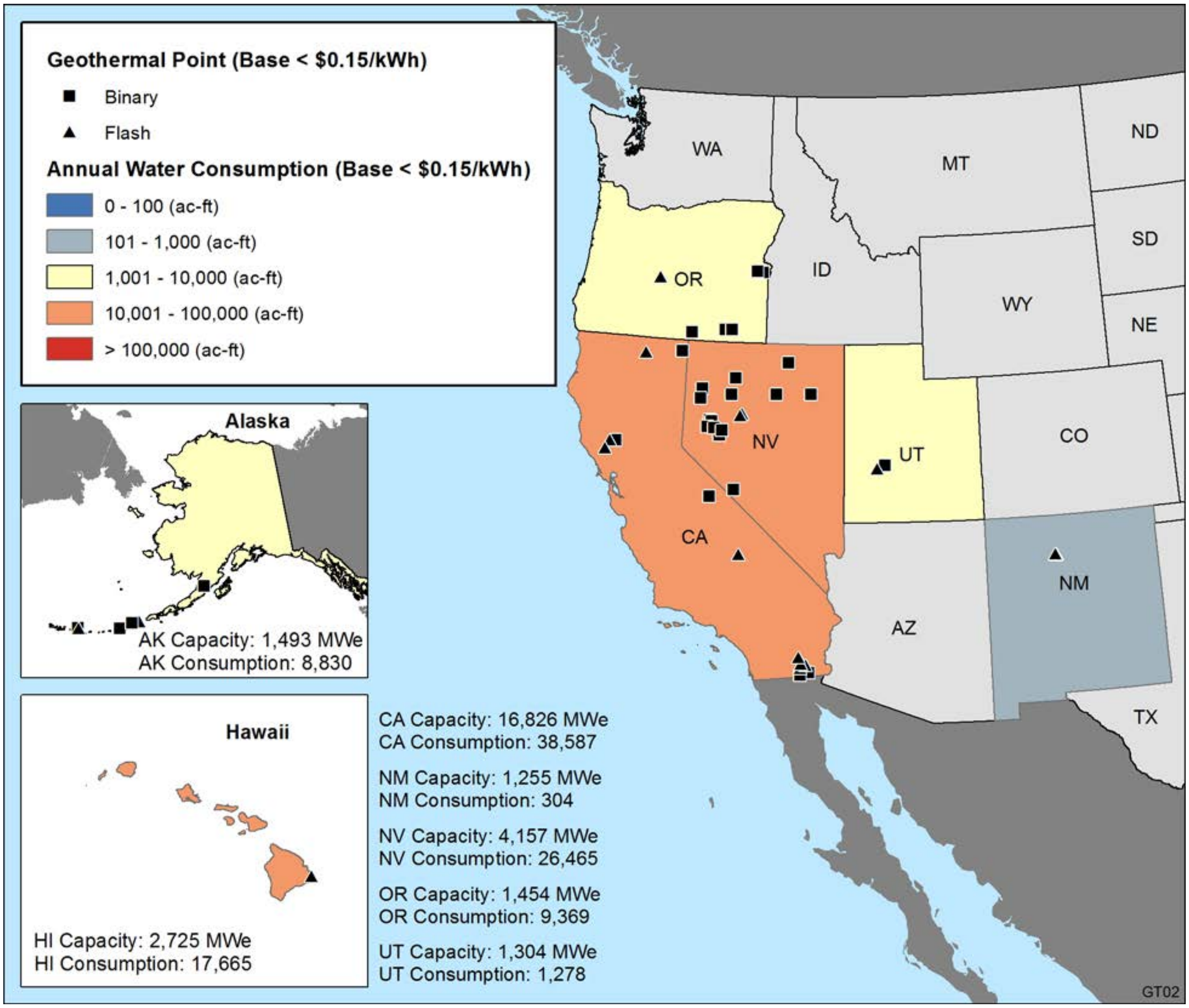

FIGURE A6 Geothermal Resources with LCOE < $0.15/kWh, Base Cost Curve.

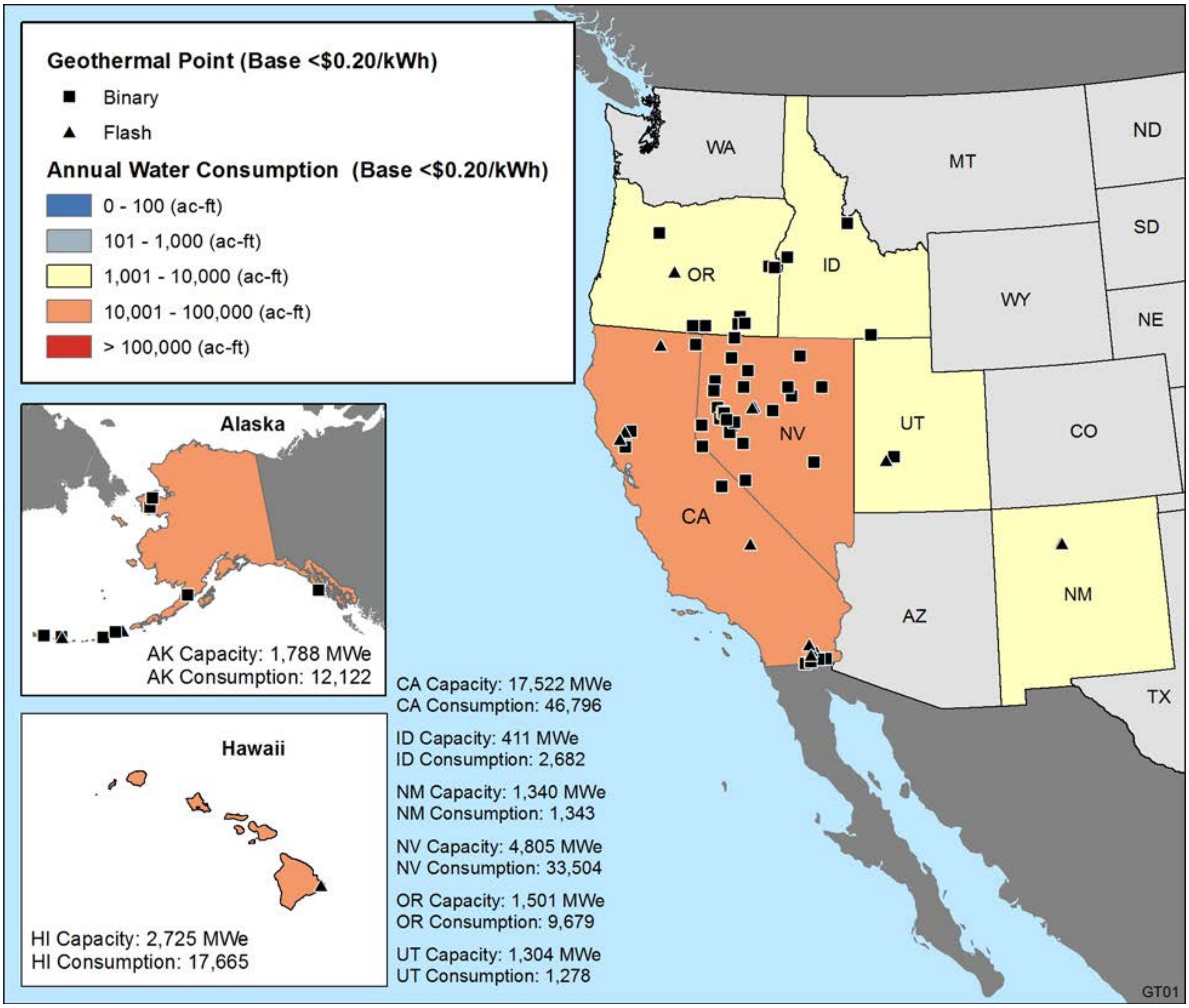

FIGURE A7 Geothermal Resources with LCOE < $0.20/kWh, Base Cost Curve.

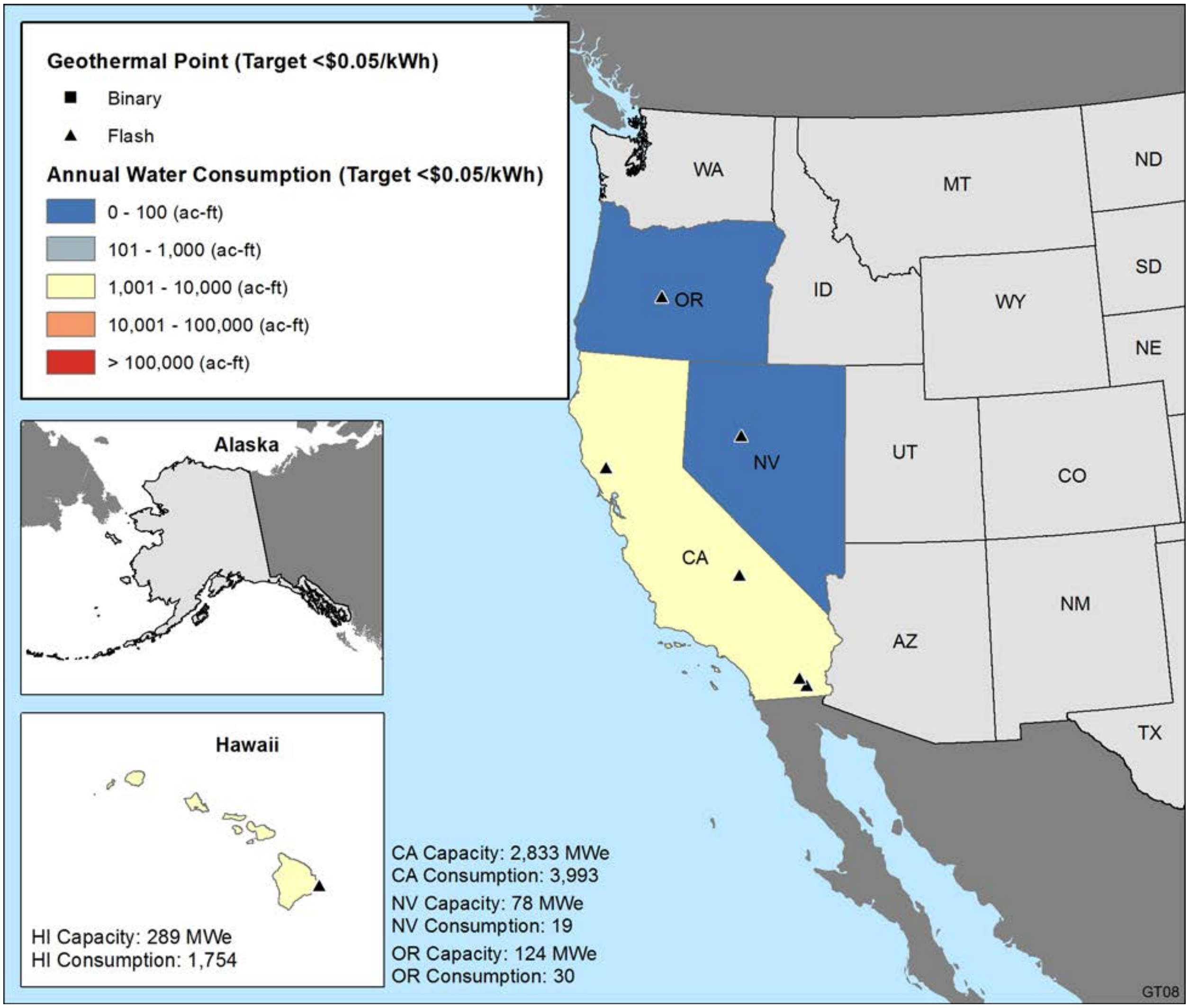

FIGURE A8 Geothermal Resources with LCOE < $0.05/kWh, Target Cost Curve.

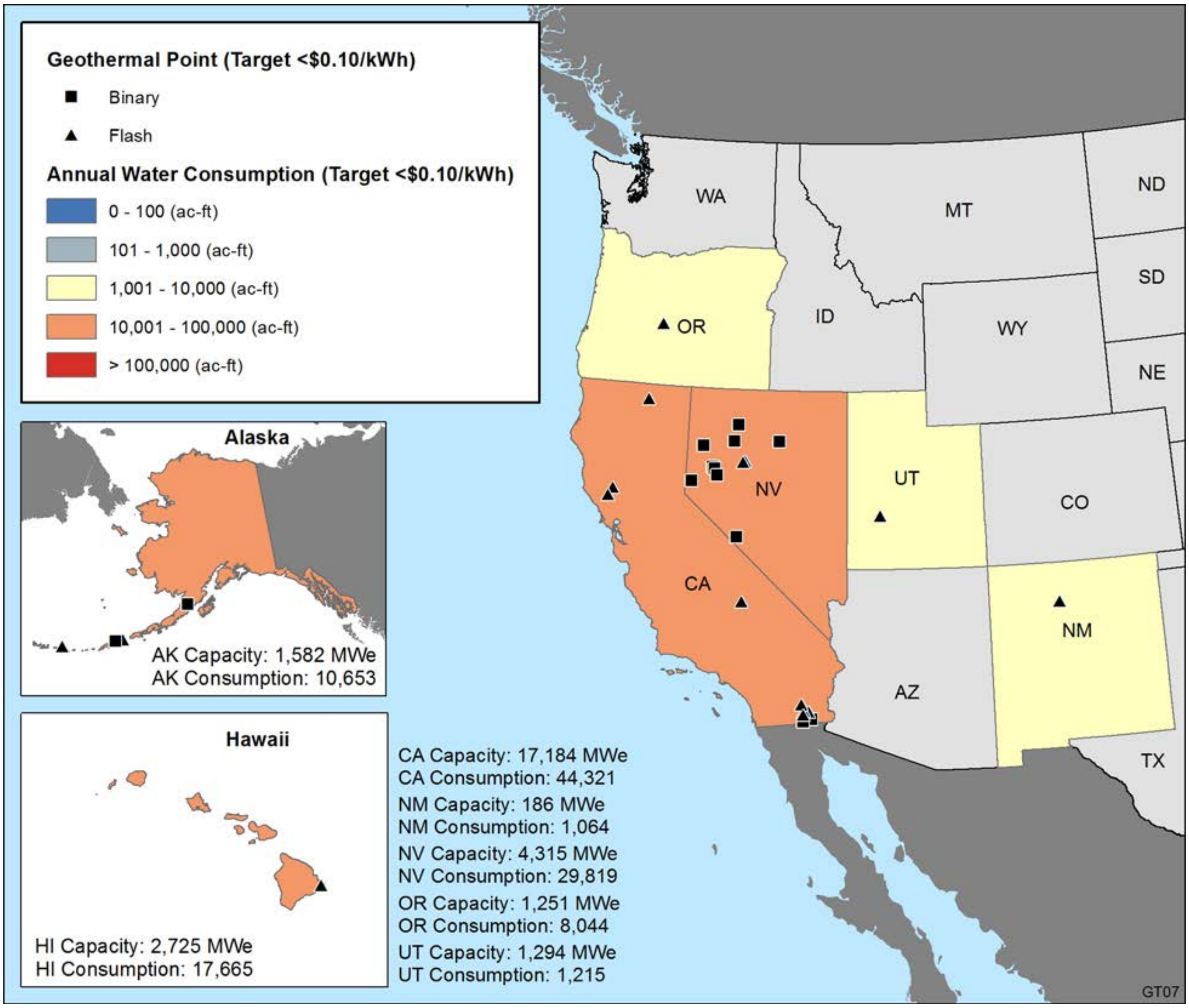

FIGURE A9 Geothermal Resources with LCOE < $0.10/kWh, Target Cost Curve.

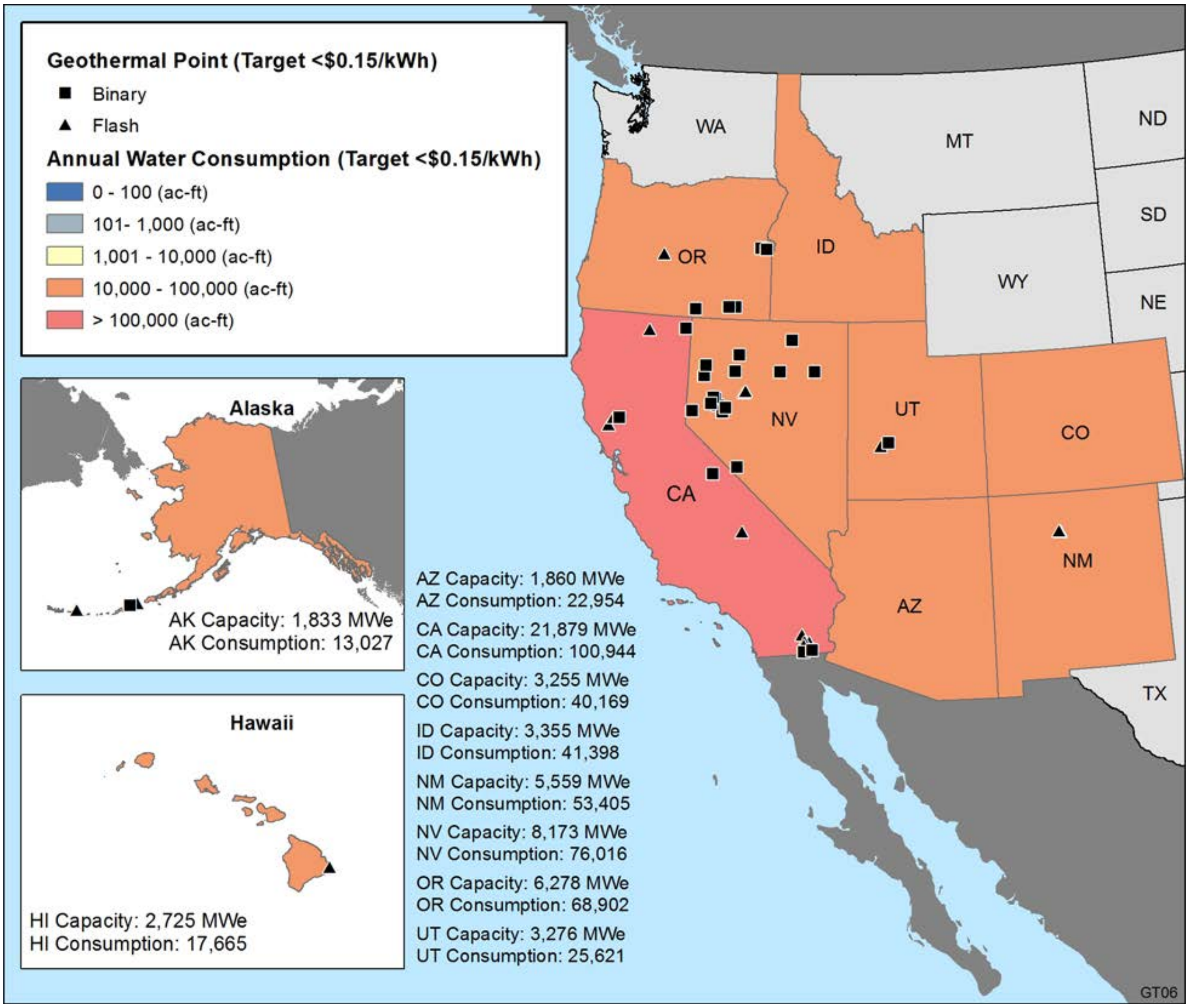

FIGURE A10 Geothermal Resources with LCOE < $0.15/kWh, Target Cost Curve.

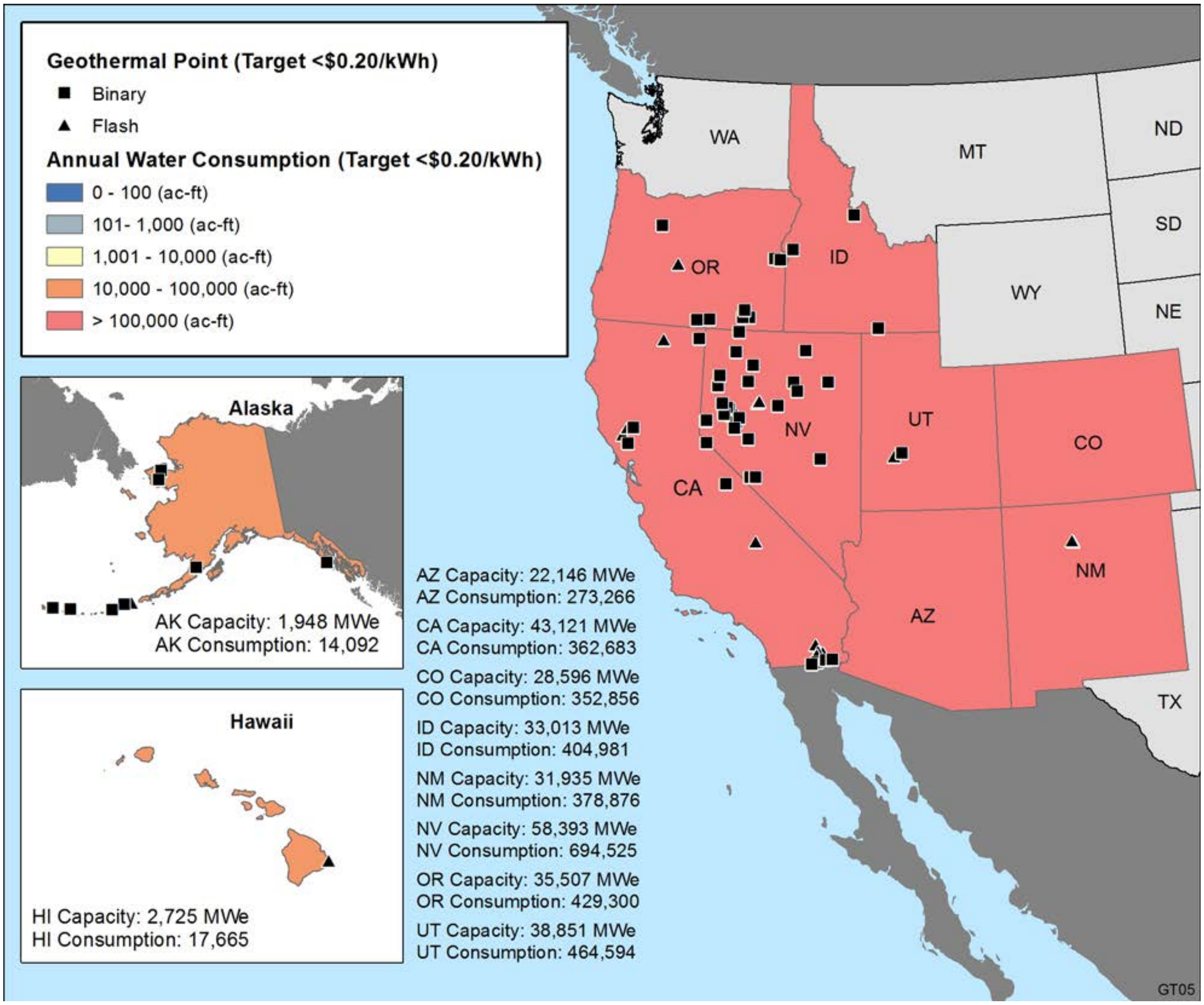

FIGURE A11 Geothermal Resources with LCOE < $0.20/kWh, Target Cost Curve.

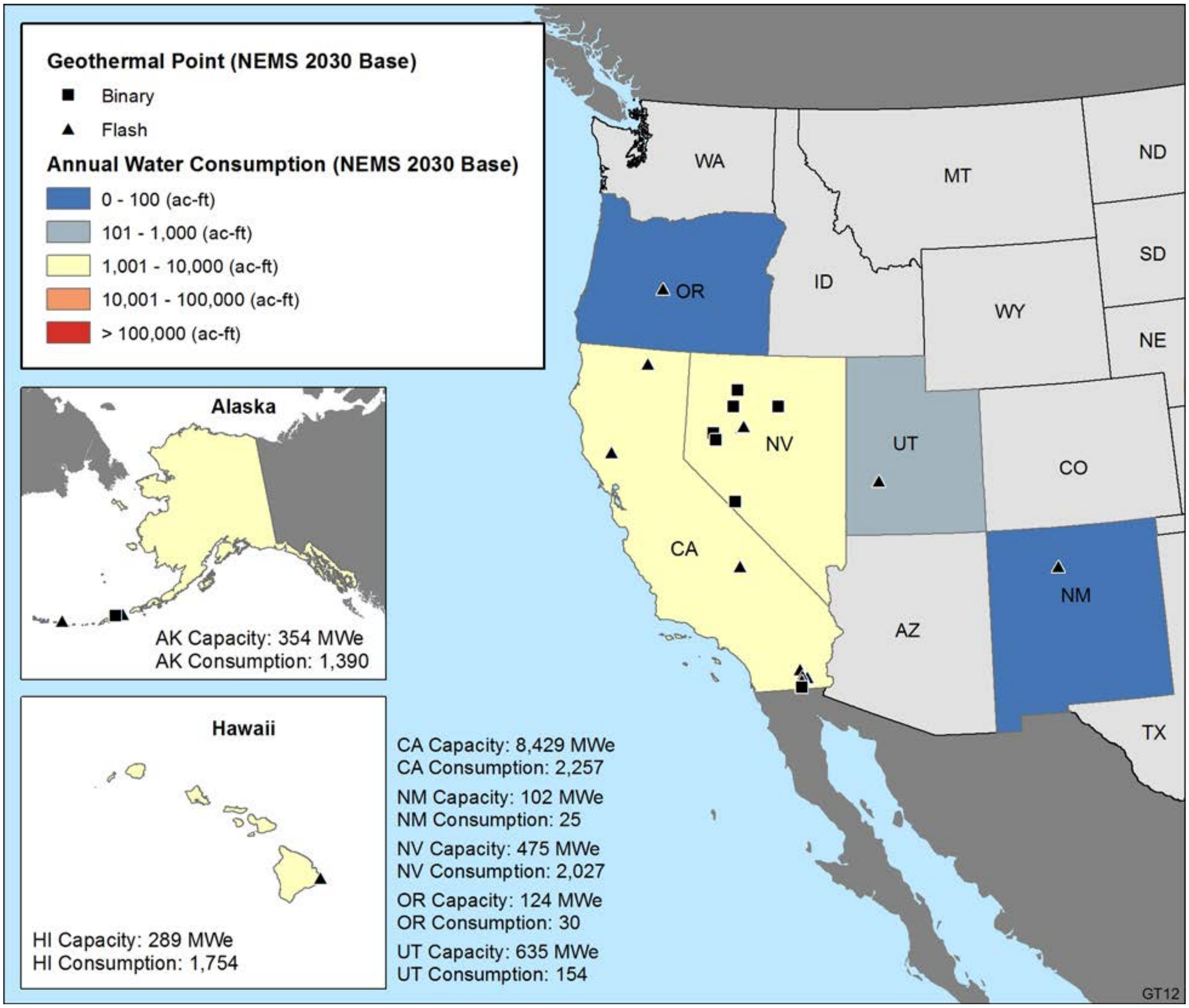

FIGURE A12 Geothermal Generating Capacity Growth, NEMS-GPRA 2030, Base Cost Curve.

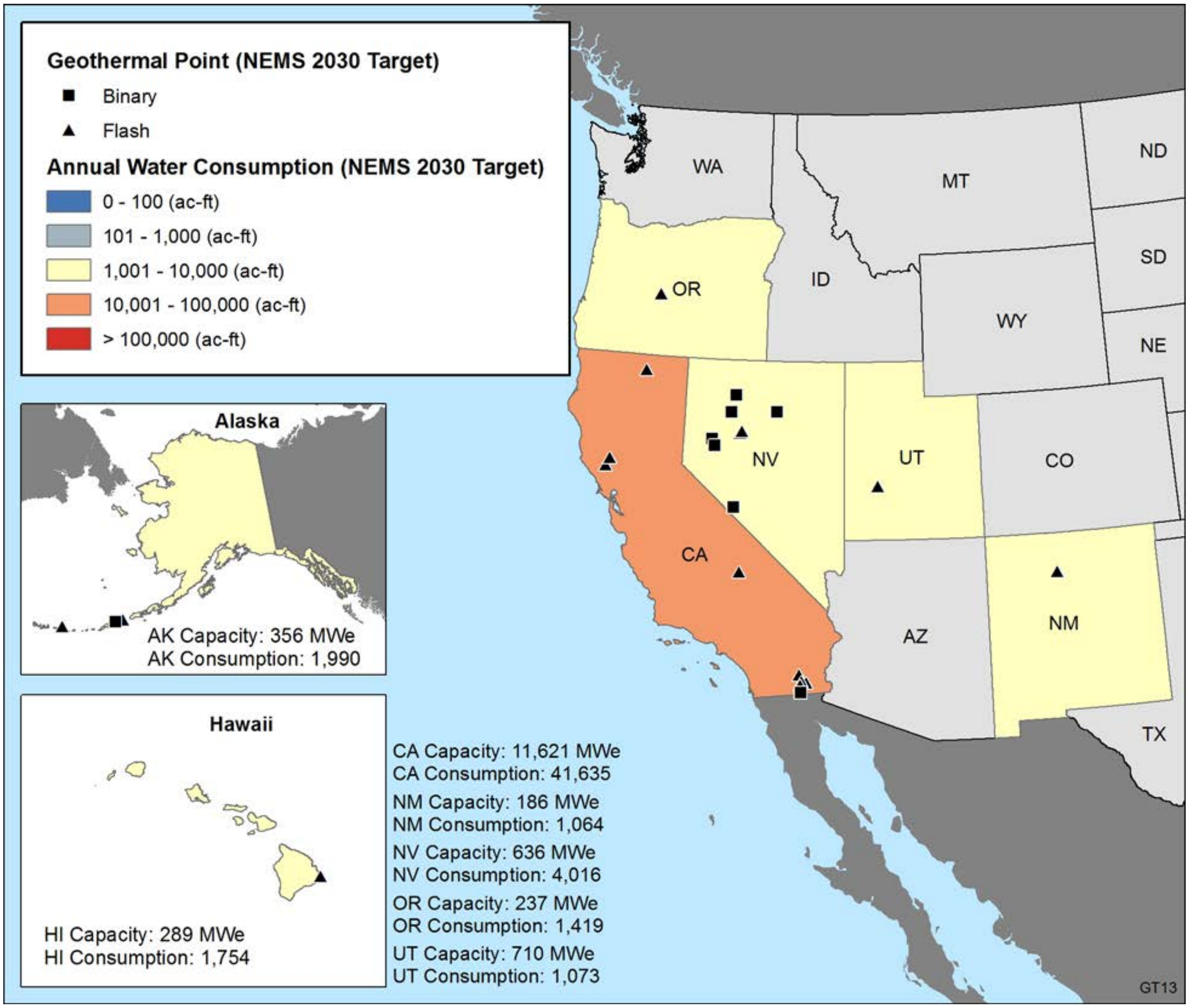

FIGURE A13 Geothermal Generating Capacity Growth, NEMS-GPRA 2030, Target Cost Curve.

APPENDIX B – WELL DESIGNS

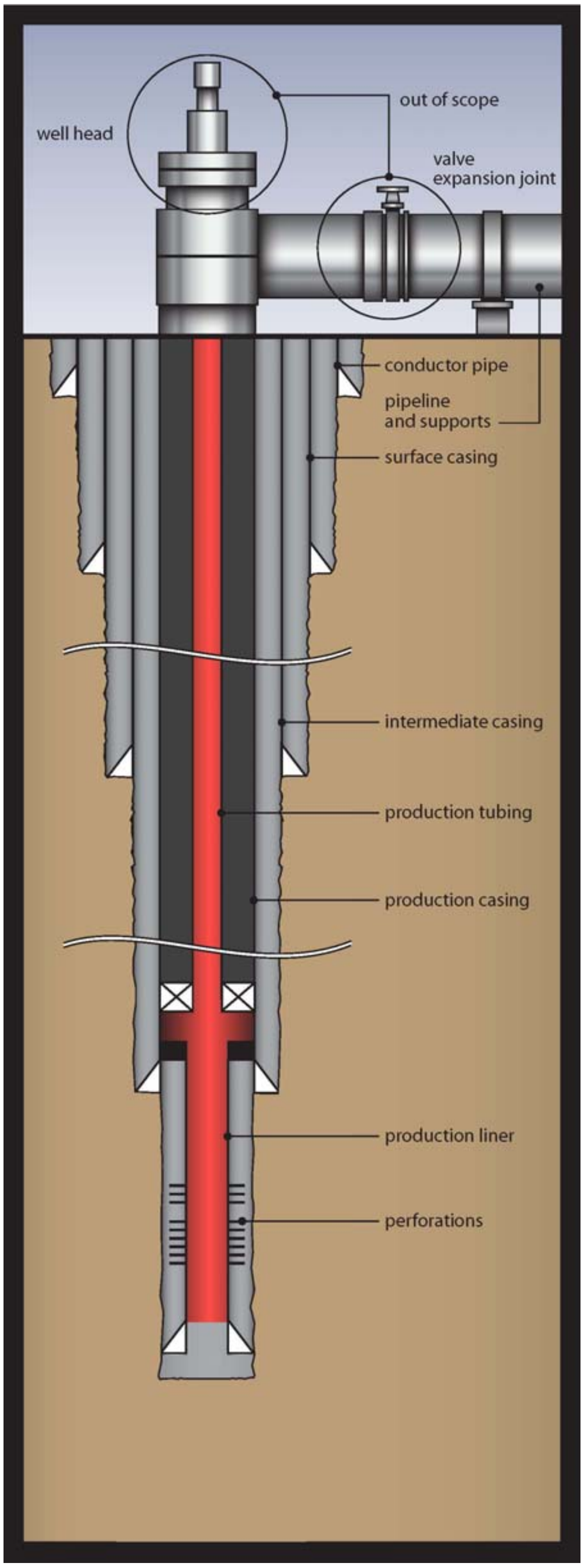

FIGURE B.1 Design for Production Well.

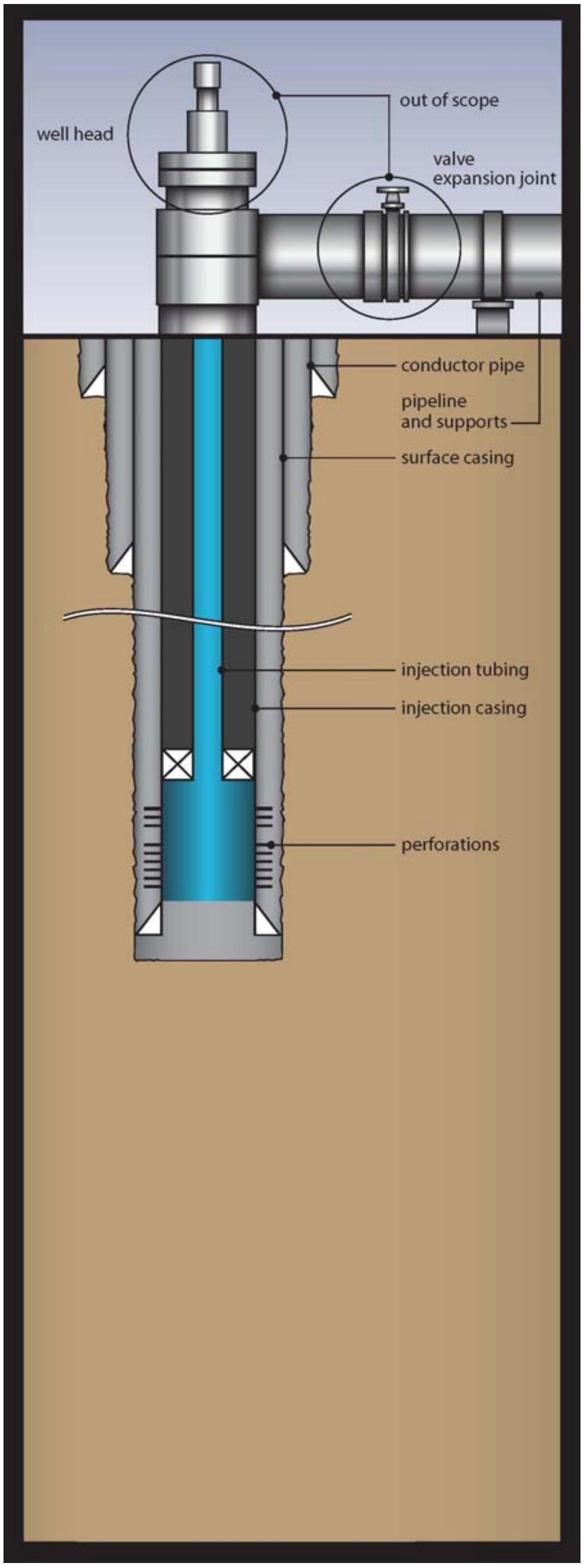

FIGURE B.2 Design for Injection Well.

TABLE B.1 Production Well Characteristics at the Considered Depths

Well Depth (km)	Casing Schedule	Material	Depth (m)	Hole (cm)	Casing (cm)	Weight/length (kg/m)
4	Conductor pipe	Welded wall	31	76.20	66.04	202.64
	Surface casing	H-40 casing and K-55 casing	338	60.96	50.80	139.89
	Intermediate casing	S-95, L-80, and N-80 casing	2,058	44.45	33.97	107.15
	Production casing	S-105, S-95, and S-105 buttress	3,463	31.12	24.45	79.62 (69.94 for S-95)
	Production liner	P-110 SHFJ liner	3,992	21.59	17.78	56.55
	Production tubing	P-110 tube	3,295	-	13.97	25.30
5	Conductor pipe	Welded wall	38	76.20	66.04	202.64
	Surface casing	H-40 casing and K-55 casing	423	60.96	50.80	139.89
	Intermediate casing	S-95, L-80, and N-80 casing	2,572	44.45	33.99	107.15
	Production casing	S-105, S-95, and S-105 buttress	4,329	31.12	24.46	79.62 (69.94 for S-95)
	Production liner	P-110 SHFJ liner	4,989	21.59	17.78	56.55
	Production tubing	P-110 tube	4,119	-	13.97	25.30
6	Conductor pipe	Welded wall	46	76.20	66.04	202.64
	Surface casing	H-40 casing and K-55 casing	507	60.96	50.80	139.89
	Intermediate casing	S-95, L-80, and N-80 casing	3,086	44.45	33.99	107.15
	Production casing	S-105, S-95, and S-105 buttress	5,194	31.12	24.46	79.62 (69.94 for S-95)
	Production liner	P-110 SHFJ liner	5,987	21.59	17.78	56.55
	Production tubing	P-110 tube	4,943	-	13.97	25.30

TABLE B.2 Injection Well Characteristics for the Considered Depths

Well Depth (km)	Casing Schedule	Material	Depth (m)	Hole (cm)	Casing (cm)	Weight/length (kg/m)
2	Conductor pipe	Welded wall	20	76.20	66.04	202.39
	Surface casing	H-40 K-55 STC casing	396	60.96	50.80	139.89
	Injection casing	S-95, N-80 SSTC, and buttress casing	2,000	44.45	33.99	107.15
	Buttress	N-80 buttress casing	1,832	33.97	24.46	59.53
	Injection tubing	K-55 and J-55	1,751	-	13.97	23.07
2.5	Conductor pipe	Welded wall	25	76.20	66.04	202.39
	Surface casing	H-40 K-55 STC casing	495	60.96	50.80	139.89
	Injection casing	S-95, N-80 SSTC, and buttress casing	2,500	44.45	33.99	107.15
	Buttress	N-80 buttress casing	2,289	33.97	24.46	59.53
	Injection tubing	K-55 and J-55	2,188	-	13.97	23.07
3	Conductor pipe	Welded wall	30	76.20	66.04	202.39
	Surface casing	H-40 K-55 STC casing	593	60.96	50.80	139.89
	Injection casing	S-95, N-80 SSTC, and buttress casing	3,000	44.45	33.99	107.15
	Buttress	N-80 buttress casing	2,747	33.97	24.46	59.53
	Injection tubing	K-55 and J-55	2,626	-	13.97	23.07

APPENDIX C – SUMMARY OF WATER CONSUMPTION FOR ELECTRICITY GENERATION TECHNOLOGIES

TABLE C.1 Water Consumption Where Significant for Geothermal Power Generation at Indicated Life Cycle Stages — in gal/kWh of Lifetime Energy Output

Life Cycle Stage	Cooling System Type			Other	Reference
	Once through	Pond Cooling	Cooling towers		
Coal					
Fuel Production				0.26	Gleick 1994
Plant Operation	0.32		0.69		Gleick 1994
Plant Operation	0.3	0.3 – 0.48	0.48		Goldstein & Smith 2002
Plant Operation	0.2	0.7	0.7		Dziegielewski et al. 2004
Plant Operation			0.43 – 0.71		NETL 2005
Plant Operation			0.68		NETL 2007
Plant Operation	0.02 – 0.23	0.22	0.57 – 0.68		Yan & Dziegielewski 2004
Plant Operation	0.06 – 0.14	0.004 – 0.8	0.46		NETL 2008
Coal with Carbon Capture					
Fuel Production				0.01 – 0.17	Harto et al. 2010
Plant Construction				0.13 – 0.25	Harto et al. 2010
Plant Operation			0.30 – 0.37	0.13 – 0.14	Klett et al. 2005
Plant Operation				0.5 – 1.2	Harto et al. 2010
Total Life Cycle				0.57 – 1.53	Harto et al. 2010
Nuclear					
Fuel Production				0.14	Gleick 1994
Plant Operation			0.85		Gleick 1994
Plant Operation	0.4	0.4 – 0.72	0.72		Goldstein & Smith 2002
Plant Operation	0.4	0.5	0.8		Dziegielewski et al. 2004
Plant Operation	0.14		0.62		NETL 2008
Natural Gas Conventional					
Fuel Production				0.29	Gleick 1994
Plant Operation	0.3	0.3 – 0.48	0.48		Goldstein & Smith 2002
Plant Operation	0.29		0.69		Gleick 1994
Plant Operation	0.09	0.11	0.16		NETL 2008
Natural Gas Combined Cycle					
Fuel Production				0.22	Gleick 1994
Plant Operation	0.1		0.18		Goldstein & Smith 2002
Plant Operation			0.27		NETL 2007
Plant Operation			0.5		NETL 2005
Plant Operation			0.28	0.09	Klett et al. 2005
Plant Operation			0.32		CEC 2006
Hydroelectric					
Dam	4.5				Gleick 1992

TABLE C.1 (Cont.)

	Cooling System Type				
Life Cycle Stage	**Once-through**	**Pond Cooling**	**Cooling towers**	**Other**	**Reference**
Solar Thermal (Concentrated Solar Power)					
Plant Construction				0.02 – 0.08	Harto et al. 2010
Plant Operation				0.77 – 0.92	Harto et al. 2010
Plant Operation			0.73 – 1.06	0.03 – 0.35	Macknick et al. 2011
Plant Operation			0.56 – 0.85		DeMeo & Galdo 1997
Total Life Cycle				0.87 – 1.12	Harto et al. 2010
Solar Photovoltaic					
Plant construction				0.06 – 0.15	Harto et al. (2010)
Plant operation				0.006 – 0.02	Harto et al. (2010)
Plant operation				0.026 – 0.033	Macknick et al. (2011)
Total life cycle				0.07 – 0.19	Harto et al. (2010)
Wind Onshore					
Plant construction				0.02	Vestas (2006)
Plant operation				3.62E-08	Vestas (2006)
Total life cycle[a]				0.01	Vestas (2006)
Biomass					
Plant operation	0.3	0.3 – 0.48	0.48		Goldstein & Smith (2002)
Plant operation			0.61		Gleick (1994)
Geothermal – EGS					
Plant construction				0.01	Clark et al. (2011)
Plant construction				0.29	Frick et al. (2010)
Plant operation				0.29 – 0.72	Clark et al. (2011)
Plant operation			0.08		Frick et al. (2010)
Geothermal – Binary[b]					
Plant construction				0.001	Clark et al. (2011)
Plant operation				0.27	Clark et al. (2011)
Plant operation	0.15				Adee & Moore (2010)
Geothermal – Flash[b]					
Plant construction				0.001	Clark et al. (2011)
Plant operation				0.005	Clark et al. (2011)
Plant operation			0.01		Adee & Moore (2010)
Geothermal – Geopressured					
Plant construction				4E-04 – 5E-04	Argonne[c]

[a] Assumes recovery of water in the end-of-life management stage.

[b] Assumes water consumed as makeup for operational loss is a small percentage of total operational geofluid loss.

[c] Results are from the present report.

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