ANL/EVS/R-12/8

Life Cycle Water Consumption and Water Resource Assessment for Utility-Scale Geothermal Systems: An In-Depth Analysis of Historical and Forthcoming EGS Projects

Environmental Science Division

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NOTATION

The following is a list of acronyms, abbreviations, and units of measure used in this document. Some acronyms used only in tables may be defined only in those tables.

GENERAL ACRONYMS AND ABBREVIATIONS

AGGD	Argonne Geothermal Geochemical Database
BLM	Bureau of Land Management
CID	Coachella Irrigation District
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
EA	environmental assessment
EGS	enhanced geothermal system
EIA	Energy Information Administration
EIS	environmental impact statement
EPA	U.S. Environmental Protection Agency
GETEM	Geothermal Electricity Technology Evaluation Model
GIS	geographic information system
GPRA	Government Performance and Results Act of 1993
GWPC	Groundwater Protection Council
HUC	hydrologic unit code
IID	Imperial Irrigation District
INL	Idaho National Laboratory
LCA	life cycle analysis
LCOE	levelized cost of electricity
NCG	noncondensable gas
NDWR	Nevada Division of Water Resources
NEPA	National Environmental Policy Act of 1969
NEMS	National Energy Modeling System
NREL	National Renewable Energy Laboratory
OCA-HT	organic clay for high temperature

RMA	regular mud acid
TDS	total dissolved solids
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

CHEMICALS

Ca	calcium
HCl	hydrochloric acid
HF	hydrofluoric acid
K	potassium
Mg	magnesium
NaCl	sodium chloride
NH_4Cl_3	ammonium chloride
SO_4^{2-}	sulfate

UNITS OF MEASURE

ac-ft	acre foot (feet)
°C	degree(s) Celsius
°F	degree(s) Fahrenheit
ft	foot (feet)
ft^3	cubic foot (feet)
gal	gallon(s)
gpm	gallons per minute
GW	gigawatt(s)
GWe	gigawatt(s) electric
kg	kilogram(s)
km	kilometer(s)
km^2	square kilometer(s)
km^3	cubic kilometer(s)
kWh	kilowatt hour(s)

L	liter(s)
m	meter(s)
m^3	cubic meter(s)
mg	milligram(s)
mm	millimeter(s)
MPa	megapascal(s)
MW	megawatt(s)
MWe	megawatt(s) electric
ppm	parts per million
psi	pounds per square inch
s	second(s)
scf	standard cubic feet
stb	stock tank barrel
yr	year(s)

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EXECUTIVE SUMMARY

This report is the third in a series of reports sponsored by the U.S. Department of Energy Geothermal Technologies Program in which a range of water-related issues surrounding geothermal power production are evaluated. The first report made an initial attempt at quantifying the life cycle fresh water requirements of geothermal power-generating systems and explored operational and environmental concerns related to the geochemical composition of geothermal fluids. The initial analysis of life cycle fresh water consumption of geothermal power-generating systems identified that operational water requirements consumed the vast majority of water across the life cycle. However, it relied upon limited operational water consumption data and did not account for belowground operational losses for enhanced geothermal systems (EGSs). A second report presented an initial assessment of fresh water demand for future growth in utility-scale geothermal power generation. The current analysis builds upon this work to improve life cycle fresh water consumption estimates and incorporates regional water availability into the resource assessment to improve the identification of areas where future growth in geothermal electricity generation may encounter water challenges.

This report is divided into nine chapters. Chapter 1 gives the background of the project and its purpose, which is to assess the water consumption of geothermal technologies and identify areas where water availability may present a challenge to utility-scale geothermal development. 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. The geothermal electricity generation technologies evaluated in this study include conventional hydrothermal flash and binary systems, as well as EGSs that rely on engineering a productive reservoir where heat exists, but where water availability or permeability may be limited.

Chapter 2 describes the approach and methods for this work and identifies the four power plant scenarios evaluated: a 20-MW EGS binary plant, a 50-MW EGS binary plant, a 10-MW hydrothermal binary plant, and a 50-MW hydrothermal flash plant. The methods focus on (1) the collection of data to improve estimation of EGS stimulation volumes, aboveground operational consumption for all geothermal technologies, and belowground operational consumption for EGS; and (2) the mapping of the geothermal and water resources of the western United States to assist in the identification of potential water challenges to geothermal growth.

Chapters 3 and 4 present the water requirements for the power plant life cycle. Chapter 3 presents the results of the current data collection effort, and Chapter 4 presents the normalized volume of fresh water consumed at each life cycle stage per lifetime energy output for the power plant scenarios evaluated. Over the life cycle of a geothermal power plant, from construction through 30 years of operation, the majority of water is consumed by plant operations. For the EGS binary scenarios, where dry cooling was assumed, belowground operational water loss is the greatest contributor depending upon the physical and operational conditions of the reservoir. Total life cycle water consumption requirements for air-cooled EGS binary scenarios vary between 0.22 and 1.85 gal/kWh, depending upon the extent of belowground operational water consumption. The air-cooled hydrothermal binary and flash plants experience far less fresh water consumption over the life cycle, at 0.04 gal/kWh. Fresh water requirements associated with air-

cooled binary operations are primarily from aboveground water needs, including dust control, maintenance, and domestic use. Although wet-cooled hydrothermal flash systems require water for cooling, these plants generally rely upon the geofluid, fluid from the geothermal reservoir, which typically has high salinity and total dissolved solids concentration and is much warmer than normal groundwater sources, for their cooling water needs; thus, while there is considerable geofluid loss at 2.7 gal/kWh, fresh water consumption during operations is similar to that of air-cooled binary systems.

Chapter 5 presents the assessment of water demand for future growth in deployment of utility-scale geothermal power generation. The approach combines the life cycle analysis of geothermal water consumption with a geothermal supply curve according to resource type, levelized cost of electricity (LCOE), and potential growth scenarios. A total of 17 growth scenarios were evaluated. In general, the scenarios that assumed lower costs for EGSs as a result of learning and technological improvements resulted in greater geothermal potential, but also significantly greater water demand due to the higher water consumption by EGSs. It was shown, however, that this effect could be largely mitigated if nonpotable water sources were used for belowground operational water demands. The geographical areas that showed the highest water demand for most growth scenarios were southern and northern California, as well as most of Nevada.

In addition to water demand by geothermal power production, Chapter 5 includes data on water availability for geothermal development areas. A qualitative analysis is included that identifies some of the basins where the limited availability of water is most likely to affect the development of geothermal resources. The data indicate that water availability is fairly limited, especially under drought conditions, in most of the areas with significant near- and medium-term geothermal potential. Southern California was found to have the greatest potential for water-related challenges with its combination of high geothermal potential and limited water availability.

The results of this work are summarized in Chapter 6. Overall, this work highlights the importance of utilizing dry cooling systems for binary and EGS systems and minimizing fresh water consumption throughout the life cycle of geothermal power development. The large resource base for EGSs represents a major opportunity for the geothermal industry; however, depending upon geology, these systems can require large quantities of makeup water due to belowground reservoir losses. Identifying potential sources of compatible degraded or low-quality water for use for makeup injection for EGS and flash systems represents an important opportunity to reduce the impacts of geothermal development on fresh water resources. The importance of identifying alternative water sources for geothermal systems is heightened by the fact that a large fraction of the geothermal resource is located in areas already experiencing water stress.

Chapter 7 is a glossary of the technical terms used in the report, and Chapters 8 and 9 provide references and a bibliography, respectively.

1 INTRODUCTION

According to the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE), geothermal energy generation in the United States is projected to increase nearly threefold from 2.37 to 6.30 GW by 2035 (EIA 2012). This increase is anticipated because of technological advances and the increase in available sources through the continued development of *enhanced geothermal systems* (EGSs) and low-temperature resources (EIA 2012).

Although studies have shown that air emissions, *water consumption*, and land use for geothermal electricity generation have less of an impact than traditional fossil fuel–based electricity generation, the water-related impacts of geothermal electricity generation across the life cycle are still uncertain, especially for emerging EGSs. With a nearly threefold projected increase in geothermal electricity generation through the use of these new technologies, it is important to understand the potential impacts and the potential differences between EGSs and more traditional hydrothermal systems. This work builds upon previous work examining life cycle water consumption for various geothermal technologies to better estimate water consumption across the life cycle for these technologies and to assess the potential water challenges that future geothermal power generation projects may face.

1.1 PURPOSE

This project is divided into two parts. The objectives of the first part of this work were to examine past and existing geothermal projects to improve operational water consumption estimates, both of aboveground consumption (all evaluated technologies) and belowground consumption (EGS only); identify water management practices associated with EGS stimulation activities; and identify water quality issues or barriers to EGS development. The results of part one informed a *life cycle analysis* (LCA) of water consumption. The life cycle water consumption results were then integrated with potential geothermal growth scenarios in part two. The objectives of the second part of this work were to examine water consumption by geothermal projects at a regional scale, to estimate the future water demand of these systems, and to identify potential water challenges that projects may face in areas where water scarcity is already a concern. The three general types of geothermal systems evaluated in this report are described in Appendix A.[1]

1.2 OVERVIEW AND UPDATES FROM PREVIOUS STUDY

Previously, Argonne National Laboratory (Argonne) considered the life cycle water requirements of geothermal electric power generation systems and the water quality of geothermal waters (Clark et al. 2011). The life cycle water analysis revealed that the

[1] Data presented in Appendices A through F can be found at the Geothermal Data Repository at https://gdr.openei.org/.

consumptive losses during operations were significant to the overall water requirements of geothermal power plants. Although flash systems appeared to be more water efficient because of their reliance on fluid from the geothermal reservoir (*geofluid*) for cooling, the long-term sustainability of a reservoir under such conditions is uncertain. Binary systems were found to help mitigate operational and environmental concerns related to geofluids by eliminating gas venting to the atmosphere, reducing the carbon footprint and the need for hydrogen sulfide controls, and minimizing some of the key drivers of scale formation. The geothermal technologies considered also appear to consume less water on average over the lifetime energy output than most conventional electricity generation technologies, at least when utilizing dry or hybrid cooling systems.

This report builds upon that work and addresses several limitations of the previous report. The operational stage of the power plant was found to consume the majority of water for EGS, flash, and binary systems, yet the volumes consumed were based on very limited data. The data collection effort was expanded for this report to provide greater resolution on operational water use. Argonne also conducted an extensive review of existing geothermal projects to compare the estimated construction stage water requirements in the last report with anticipated consumption values in available environmental documentation for existing and planned projects. Since the publication of the previous report, several EGS projects have submitted planning documentation and many have stimulated wells. Argonne also examined these projects, both national and international EGS projects, to improve volume estimates for reservoir stimulation and belowground operational loss.

2 APPROACH AND METHODS

The following approaches were used to collect data from past and existing geothermal projects: (1) a traditional literature review, (2) a review of documentation required by the National Environmental Policy Act of 1969 (NEPA), (3) a review of available environmental documentation of international EGS projects, and (4) an examination of permits and monthly production and injection records for operational water use estimates. The data were incorporated into an existing LCA to improve estimates of water consumption by geothermal technologies.

2.1 LITERATURE REVIEW

The literature search was conducted by using a number of databases via the tool Engineering Village. Engineering Village is a web-based information service that accesses Compendex, GEOBASE®, and GeoRef databases. Compendex is a bibliographic database of scientific and technical engineering research that covers various engineering disciplines. GEOBASE is a database of research literature covering the earth sciences and includes topical areas such as alternative energy sources, environmental sciences, geology, and physical geography. GEOBASE has an international coverage of peer-reviewed journals, trade publications, book series, and conference proceedings. The American Geological Institute's GeoRef database has a geology focus and contains more than 2.9 million records. The search was limited to the period from 1990 until the present and focused on the following key terms: geothermal water use, hot dry rock, enhanced geothermal system, and geothermal boring.

The titles and abstracts of the studies identified in these searches were reviewed to determine which documents should be examined in their entirety. Studies that describe both conventional geothermal energy technology and enhanced geothermal energy technology were included in the review.

2.2 NEPA DOCUMENTATION REVIEW

A comprehensive review of relevant environmental documentation, including documents produced by NEPA and similar documentation for international EGS projects, was conducted as a means of obtaining water usage information about geothermal projects. This review was meant to capture information that a traditional literature review might miss, as well as to complement such a review.

NEPA requires completion of an environmental assessment (EA) and/or environmental impact statement (EIS) for any major action by a federal agency that may affect the environment. Because many geothermal projects in the western United States occur on lands owned by the federal government, which are then subsequently leased for development, the NEPA documentation review was begun by systematically researching geothermal projects through the U.S. Department of the Interior (DOI) Bureau of Land Management (BLM) on a state-by-state basis. Starting with Nevada, BLM field office web sites were searched for available NEPA

documents. In addition, documents from older projects and/or documents that had not been posted online yet were requested from the relevant field office as needed. In addition to a thorough search of BLM documents, the DOE Office of NEPA Compliance also produced documentation in cases where the geothermal project had received DOE funds but was potentially not on federal land.

This process was conducted for states with active geothermal areas—Alaska, Arizona, California, Idaho, Nevada, Oregon, and Utah. Altogether, 34 NEPA documents representing 38 separate geothermal projects were obtained. Many projects that were initially identified ended up occurring on private land, which means that the NEPA process was not triggered; thus no documentation was produced. Also, many projects were old enough that the NEPA documents that were available contained very little information about water usage, since it was not as prevalent to include such information in the 1970s, 1980s, and even parts of the 1990s.

2.3 DOCUMENTATION REVIEW OF INTERNATIONAL PROJECTS

In addition to collecting NEPA documents for geothermal work in the United States, similar environmental documentation for international EGS projects was also collected. International EGS projects were included to increase the total number of EGS projects evaluated. Projects identified were located in Australia, France, Germany, Japan, Sweden, Switzerland, and the United Kingdom, for a total of 12 international EGS projects. Documentation ranged from detailed environmental impact reports to more generalized information in the scientific literature.

2.4 OTHER RESOURCES FOR DATA

To improve estimates for operational water loss, a concerted effort was made to obtain new data. Data used in Clark et al. (2011) were limited to those made available by the California Department of Conversation, Division of Oil, Gas, and Geothermal Resources (2010). In addition to incorporating operational water use data as described in environmental documentation such as EAs or EISs, data were also obtained from the Nevada Division of Minerals and the Nevada Division of Water Resources.

The Nevada Division of Minerals makes production and injection data available for geothermal power plants across the state. The data are self-reported by the facility's operator on a monthly basis for each production and injection well used at the plant. By comparing production and injection data within 1 month, makeup or loss rates were established for each facility. Data were collected for 19 facilities.

To provide a comparison for the production and injection data, applicable water permits issued by the State of Nevada were retrieved through the Nevada Division of Water Resources Permit Search web portal (http://water.nv.gov/data/permit/index.cfm). Permitted water usage could then be compared with makeup and loss rates from the self-reported data collected by the Nevada Division of Minerals.

2.5 ORGANIZATION OF DATA

Once documentation was obtained from these different sources, relevant information such as project location, stage of project, type of geothermal system, well depth, amount of water consumed, water quality impacts, information about reservoir loss, and other data were entered into a database to organize and compile the information. This was done so that the information would be well organized and thus easily searchable for later stages of this analysis. This database will be referred to as the Project Database throughout this report.

For the environmental documentation review, of the more than 50 domestic geothermal projects identified and analyzed, 9 projects were identified as having an EGS component. These projects were:

- The Geysers in California;
- Desert Peak, Brady's Hot Springs, and New York Canyon in Nevada;
- Naknek in Alaska;
- Newberry Volcano in Oregon;
- Fenton Hill and Baca in New Mexico; and
- Raft River in Idaho.

Of these nine projects, work was sufficiently underway at seven—Fenton Hill, Baca, the Geysers, Newberry, Desert Peak, Raft River and Naknek—such that documentation was available. One of the projects, Brady's Hot Springs, had received approval for well stimulation at the time of this analysis; therefore, the project was in its early stages and no documentation was available. For the remaining project (New York Canyon), no information was available due to project termination in 2012.

In addition, 12 international EGS projects were identified through the combined literature and environmental documentation review:

- Paralana, Innamincka Deep, Innamincka Shallows, and Penola in Australia;
- Soultz in France;
- Basel in Switzerland;
- Rosemanowes in the United Kingdom;
- Bad Urach and Groβ Schönebeck in Germany;
- Fjallabacka in Sweden; and

- Ogachi and Hijiori in Japan.

Documentation on all these projects was also included in the Project Database.

Figure 1 shows a summary of the breakdown of the documentation review included in the Project Database. Of the 478 total entries, the majority were environmental permits. This group represents approximately 78% (or 373 documents) of the total entries made. The next largest group was NEPA documents, with 34 entries, or 7% of the database. Journal articles, which represented 5% (or 24 entries) of the database, and conference papers and proceedings, which represented 5% (or 22 entries) of the database, were also notable.

2.6 LIFE CYCLE ANALYSIS

A process-based LCA was conducted to account for *fresh water* consumption and considered activities associated with drilling, stimulation, construction, and operating the wells and the power plant. In assessments of water use at power plants, two water quantities are commonly listed: water withdrawn and water consumed. Withdrawn water is defined as water that is taken from ground or surface water sources and may or may not be returned to the water source. It is most often associated with once-through cooling towers in thermoelectric power plants. Consumed water is water that is withdrawn but not returned to its area of extraction in

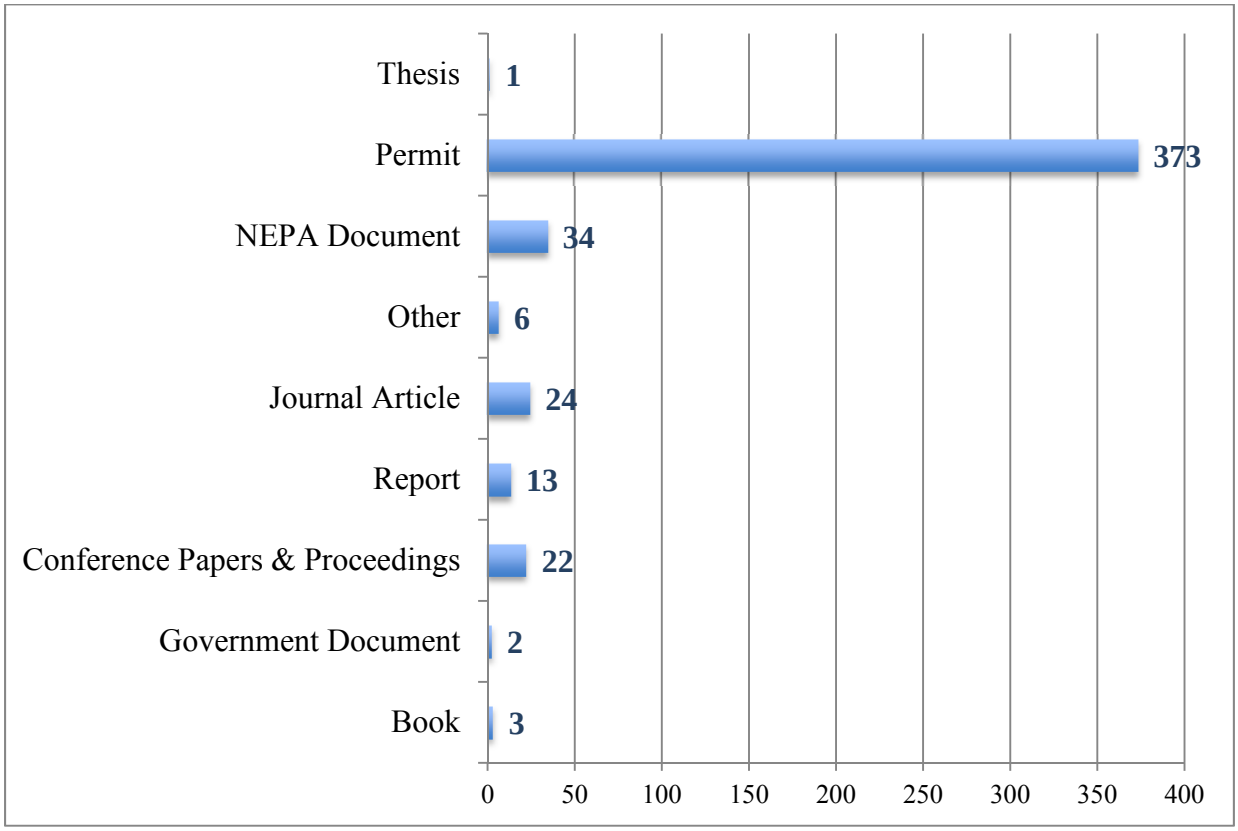

FIGURE 1 Types of References Used for This Analysis

liquid form. Water may be consumed through evaporation, chemical reactions, incorporation into materials (e.g., in drilling muds and cement), or injection into nonaquifer geological formations (e.g., stimulation or reservoir makeup fluids).

This analysis accounts for geofluid from the reservoir that is lost but not replaced separately from fresh water consumption. Losses to the atmosphere via evaporation at hydrothermal flash plants or to the formation due to reservoir characteristics may affect the long-term sustainability of such projects. They are unlikely to impact local or regional fresh water availability, however, unless supplementary injection is used to make up for these losses.

Argonne developed five power plant scenarios with input from experts in industry and other national laboratories as shown in Table 1. For consistency, these scenario parameters are unchanged from previous studies (Clark et al. 2011, 2012). The scenarios were modeled in the DOE's Geothermal Electricity Technology Evaluation Model (GETEM), and the simulation was run multiple times in GETEM to create a range of possible outcomes (EIA 2011). Water consumption estimates were then determined from the system model. This work focused on improving estimates for consumption in the EGS and hydrothermal scenarios in each critical stage of the life cycle. While a geopressured scenario is included in the LCA results, this technology was not a major focus of this effort, and the results of the previous analysis for this system are presented without significant changes (Clark et al. 2012).

2.7 REGIONAL WATER RESOURCE ASSESSMENT

The regional water resource assessment builds upon previous Argonne work that explores the geospatial distribution of water demand for future geothermal power production (Clark et al. 2012). The current analysis makes four key improvements upon the previous analysis: (1) increases the spatial resolution of the analysis, (2) updates the water consumption factors based upon the water LCA results presented in this report, (3) adds growth scenarios, and (4) includes metrics on water availability. The spatial resolution is increased from states to local watersheds as defined by the four-digit U.S. Geological Survey (USGS) hydrologic unit codes (HUC 4). The use of USGS HUC 4 basins as a unit of analysis allowed for more direct comparison with other water demand and availability data that are often presented on the basis of hydrological basins. The HUC 4 resolution was selected over the lower HUC 2 resolution and higher HUC 6 and HUC 8 resolutions. This was done to balance the desire for higher resolution analysis without increasing the resolution beyond the level of confidence in the projections of the location of future geothermal development.

The regional water resource assessment combines the LCA results presented in Chapter 4 with a detailed supply curve for geothermal resources developed by the National Renewable Energy Laboratory (NREL) (Augustine et al. 2010). On the basis of what was known about the resources, NREL used the GETEM (DOE 2011) to model the electricity generation capacity (MWe) and estimate the *levelized cost of electricity* (LCOE; $/kWh). The LCOE was estimated by using two sets of cost assumptions: (1) a "base" case that assumed current costs with minimal technological improvements; and (2) a "target" case that assumed a reduction in cost over time for EGSs resulting from learning and technological improvement due to continued federal

TABLE 1 Geothermal Technology Power Plant Scenarios Developed for Argonne's Analysis

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Geothermal technology	EGS	EGS	Hydrothermal	Hydrothermal	Geopressured
Net power output (MW)	20	50	10	50	
Producer-to-injector ratio	2:01	2:01	3:1 and 2:1	3:1 and 2:1	2:01
Number of turbines	Single	Multiple	Single	Multiple	Single
Generator type	Binary	Binary	Binary	Flash	Binary
Cooling	Air	Air	Air	Evaporative	Air
Temperature (°C)	150–225	150–225	150–185	175–300	130–150
Thermal drawdown (%/yr)	0.3	0.3	0.4–0.5	0.4–0.5	0
Well replacement	1	1	1	1	0
Exploration wells	1	1 or 2	1	1	0
Well depth (km)	4–6	4–6	<2	1.5, <3	4–6 (producers) 2–3 (injectors)
Flow rate per well (kg/s)	30–90	30–90	60–120	40–100	35–55
Gas/brine ratio (scf/stb)	NA[a]	NA	NA	NA	25–35
Pumps for production	Submersible 10,000 ft	Submersible 10,000 ft	Lineshaft or submersible	None	None
Distance between wells (m)	600–1,000	600–1,000	800–1,600	800–1,600	1,000
Location of plant in relation to wells	Central	Central	Central	Central	Central
Plant lifetime (yr)	30	30	30	30	30

[a] NA = not applicable.

investment in research, development, and demonstration projects (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.

Within the geothermal supply curve, geothermal resources are broken down into four resource categories: *identified hydrothermal, unidentified hydrothermal, near-field EGS, and deep EGS*. Identified hydrothermal resources are resources that are known to exist and that are capable of supporting hydrothermal geothermal power systems. Unidentified hydrothermal resources are resources that are likely to exist but that have not been verified. Near-field EGS resources are associated with identified hydrothermal resources but may require additional stimulation to be exploited. Deep EGS resources are hot rock formations often found at depths greater than 4 km (2 mi) and require stimulation to create fractures for fluid circulation for power generation. For the purposes of this study, these resources will be referred to as "*greenfield EGS" resources* to better differentiate them from near-field EGS resources. Geothermal resources in sedimentary formations not previously identified as hydrothermal resources were included within the greenfield EGS category and were not considered separately because of data limitations at the time that the supply curve analysis was performed. 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 improve.

The resolution of location information available within the NREL supply curve dataset 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. Greenfield EGS resources are specified by temperature and depth along with the region code for the National Energy Modeling System (NEMS) model. These region codes cover many states. In order to perform analysis based upon USGS HUC 4 basins, the unidentified hydrothermal and greenfield EGS resources were interpolated to increase the spatial resolution by using temperature at depth maps developed by Idaho National Laboratory and Southern Methodist University (INL 2011).

Both the unidentified hydrothermal and greenfield EGS resources were defined in the supply curve by a temperature and depth range for a given state or NEMS region code. The total area within the specified state or NEMS region was calculated where the temperature was within the specified range from the temperature data for the specified depth for each resource defined within the supply curve. These areas were then apportioned to the overlying HUC 4 basins. The generation capacity for the resource was then allocated to these HUC 4 basins in direct proportion to the calculated resource areas. Temperature data were available for depths of 3, 4, 5, 6, and 10 km (1.8, 2, 3, 4, and 6 mi). For depths between 6 and 10 km (4 and 6 mi) and less than 3 km (1.8 mi), temperatures were interpolated or extrapolated based upon trends calculated from the existing data with a geospatial tool called a Raster Calculator.

Water consumption factors based upon the LCA results presented in Chapter 4 were then applied to the resources within the supply curve depending upon system type (EGS, hydrothermal flash, and hydrothermal binary) as specified in Section 5.1. The specific growth scenarios analyzed are also discussed in detail in Section 5.1. The resources selected from the supply curve for each scenario were selected based upon the estimated LCOE for each resource by selecting the lowest cost resources first. The scenarios were mapped by utilizing geographic information system (GIS) software to illustrate the spatial distribution of water demand from the various growth scenarios.

For the different geothermal water demand scenarios, only greenfield EGS resources within NEMS regions 11, 12, and 13 were included in the supply curve and available for selection. These regions include all the states with hydrothermal or near-field EGS resources and where water availability data were available. There are greenfield EGS resources beyond these regions; however, the greenfield EGS resources included account for 52% of the total greenfield EGS resource base and 82% of the greenfield EGS resource base at depths of 6 km (4 mi) or shallower. In addition, the lowest cost greenfield EGS resource not included within the supply curve for the scenarios had an LCOE of $0.25 per kWh, even with the cost reduction assumptions in the target LCOE model, which makes them unlikely to be exploited in the near or medium term.

In addition to estimating water demand, an attempt was made to quantify the availability of water at the same HUC 4 resolution. Quantifying water availability is a more challenging task as precipitation changes from year to year and season to season, and there is no single generally accepted definition of the quantity of water that is "available" at any given time. Three different sets of metrics for water availability are presented in this report.

The first set of metrics that is presented is based upon reported USGS *streamflow* data. The USGS calculates annual streamflow based upon data from its extensive national monitoring network (USGS 2012). This metric specifies the remaining surface water flows, or net water availability, downstream of all natural and anthropogenic water consumption processes, within each basin. This water can be viewed as the maximum remaining "available" surface water within the basin; however, a certain amount of water must remain within the streams to provide natural flows for ecosystems. In addition, increased consumption of surface water in an upstream basin will also reduce flows in the downstream basins within the watershed. Only data from 1950 on were used due to significant changes in water consumption over the first half of the twentieth century in the western United States because of population growth and the construction of multiple large dams. This significantly altered trends in streamflow, making data from earlier years less representative of current trends. Streamflow data are presented as the average 10th and 3rd percentile of flow within each HUC 4 basin over the years 1950 to 2010. The 10th and 3rd percentile flows are presented to represent flow conditions under moderate and severe drought conditions, consistent with USGS streamflow drought classes, when conflicts over water can increase significantly (USGS 2012).

The other two sets of metrics for water availability are based upon data provided by Sandia National Laboratories (Tidwell 2012). Sandia has collected data directly from western states on their water demand for 2010 and estimated water demand for 2030. The dataset is

currently limited to 13 western states; however, these states overlap the majority of the geothermal resources in the continental United States with the exception of some greenfield EGS resources. Utilizing these water demand data, a metric was defined as the 2030 water demand divided by the streamflow plus 2010 water demand. The water demand is added to the streamflow in the denominator to calculate the flow that would naturally be present within the basin without human consumption. When the 2030 water demand is divided by this value, it calculates the fraction of the total flow that would naturally be present within the basin that will be consumed for human uses in 2030. This metric was mapped by using both the average streamflow and the 3rd percentile streamflow over the period from 1950 to 2010. A higher value of this metric indicates greater water stress within the basin and more limited surface water availability. Cases where this metric exceeds 1.0 would indicate either that all surface water would be consumed, or that stored surface water or groundwater must be consumed to supplement surface flows.

Sandia also provided estimates of water that is likely to be available for energy development based upon five different categories: *unappropriated surface water*, *appropriated surface water*, *potable groundwater*, *shallow brackish groundwater*, and *municipal wastewater*. Unappropriated surface water availability was determined by comparing streamflow to downstream delivery requirements when specific estimates were not provided directly by the states. Appropriated surface water availability was estimated based upon the quantity of water consumed by low-value agriculture (hay and alfalfa). A percentage of this water was assumed to be available for sale for higher-value uses. Potable groundwater availability was calculated based upon the safe yield where pumping must be less than or equal to recharge rates based upon USGS data. Shallow brackish groundwater availability was estimated by aggregating data from multiple state and USGS datasets. Municipal wastewater availability was estimated based upon discharge data from the USGS and U.S. Environmental Protection Agency (EPA) after accounting for existing uses (Tidwell 2012).

From these five metrics provided by Sandia, three aggregate metrics were mapped. The unappropriated surface water availability was mapped by itself, since this water resource is most likely the least expensive and easiest to acquire. A “total fresh water availability” metric was defined by combining the unappropriated surface water, appropriated surface water, and potable groundwater categories. Finally a “total water availability” metric was defined by combining all five categories. It should be noted that while shallow brackish groundwater and municipal wastewater are likely to have fewer competing uses, depending upon the end use, they are likely to have higher costs and may require significant additional treatment.

While no formal numerical analysis was performed to compare water demand for geothermal from the various growth scenarios with the included water availability metrics for this report, a qualitative analysis is included that identifies some of the basins where the limited availability of water is most likely to affect the development of geothermal resources. A more detailed quantitative comparison of water demand and availability, along with a focus on the cost of different water resources, will be targeted in ongoing research.

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3 RESULTS OF THE REVIEW

This section presents the results of the review of literature and environmental documentation by life cycle stage.

3.1 WATER REQUIREMENTS FOR DRILLING

The Project Database was reviewed to find instances of water volumes used for geothermal well drilling. In all, NEPA documents representing 21 separate geothermal projects contained some estimation of this kind of data. These documents were then separated based on geothermal well type; specifically, observation, exploration, or production/injection wells.

Once the well types were separated, the data were analyzed to calculate the number of gallons consumed per thousand feet drilled, which was used as the metric for comparison. Several assumptions were made to aid this analysis. First, three documents gave a daily water usage estimate but failed to give an estimate for the length of the drilling period, which made it impossible to estimate total water volume (BLM 1998; 1999; 2003; 2005; 2006a,b; 2007a,b; 2009; 2010a–e; 2011a–i; 2012). These data points were excluded. Second, if a range was given for final well depth, both endpoints of this range were used to provide a more robust comparison. Third, if a range for water volume was given, the median value of this range was used. For sizing exploration wells, if no drilling diameter was provided and it was not otherwise specified, it was assumed that the well was a conventional, full-sized exploration well and not a slim well. In the end, slim wells could not be analyzed separately as they were represented by only two data points, and it was determined that this was not sufficient information.

The analysis indicated that for the projects evaluated, *observation wells* were found to average 1,800 m^3 per 1,000 m (140,000 gal per 1,000 ft) drilled, *exploration wells* were found to average 1,860 m^3 per 1,000 m (150,000 gal per 1,000 ft) drilled, and *production/injection* wells were found to average 2,200 m^3 per 1,000 m (180,000 gal per 1,000 ft) drilled. Estimations for specific projects are provided in Tables 2 through 4.

3.2 EGS WELL STIMULATION

After a well is drilled for an EGS project, it is typically stimulated. Stimulating a well can enhance the output of the well by (1) improving near-well permeability that has been reduced by the drilling operation clogging pathways or (2) opening up paths to permeable zones not intersected by the well. Three general types of *well stimulation* are used in EGS development: *thermal*, *hydraulic*, and *chemical* stimulation. Thermal stimulation relies on the introduction of chilled water, and thus cold stress, to a geothermal reservoir. Hydraulic stimulation relies on the introduction of water or a combination of water and sand or water and gel-*proppant* fluids to a geothermal reservoir. Chemical well stimulation techniques involve the use of aqueous solutions to allow acids, bases, and *chelating agents* to be introduced into geothermal reservoirs.

TABLE 2 Water Requirements for Observation Wells

Observation Well (gal)	Depth (ft)	Consumption (gal/1,000 ft)	Source
450,000	3,000	150,000	Dixie Meadows (BLM 2011b)
450,000	3,000	150,000	Leach Hot Springs (BLM 2011f)
1,100,000	10,000	110,000	New York Canyon (BLM 2010b)
420,000	3,000	140,000	Drum Mountains (BLM 2011h)
Average estimated consumption		140,000	

TABLE 3 Water Requirements for Exploration Wells

Exploration Well (gal)	Depth (ft)	Consumption (gal/1,000 ft)	Source
900,000	8,000	110,000	Carson Lake (BLM 2008)
900,000	10,000	90,000	Carson Lake (BLM 2008)
2,600,000	10,000	260,000	Clayton Valley (BLM 2011e)
600,000	3,500	170,000	San Emidio (BLM 2010d)
378,000	9,000	42,000	Glass Mountain (MHA 2002)
2,500,000	12,000	210,000	Naknek (DOE 2010)
1,400,000	7,000	190,000	Tungsten Mountain (BLM 2012)
900,000	7,000	130,000	Buffalo Valley (BLM 2006b)
Average estimated consumption		150,000	

Water is the primary ingredient for all well stimulation activities. The amount of water required for well stimulation activities is dependent upon the well-reservoir environment and the well stimulation method(s) used. Well-reservoir characteristics factors likely to affect water requirements for well stimulation include:

- Well depth,
- Well construction,

TABLE 4 Water Requirements for Production and Injection Wells

Production/Injection Well (gal)	Depth (ft)	Consumption (gal/1,000 ft)	Source
1,400,000	10,000	140,000	Dixie Meadows (BLM 2011b)
1,400,000	6,000	230,000	Leach Hot Springs (BLM 2011f)
190,000	7,000	28,000	McGinness Hills (BLM 2011g)
1,300,000	7,000	190,000	Patua (BLM 2010c)
1,300,000	10,000	130,000	Patua (BLM 2010c)
1,500,000	10,000	150,000	Drum Mountains (BLM 2011h)
600,000	2,000	300,000	Neal Hot Springs (DOE 2009)
600,000	5,000	120,000	Neal Hot Springs (DOE 2009)
800,000	8,500	94,000	Fourmile Hill (BLM 1998)
2,000,000	5,500	360,000	Desert Peak (BLM 2003)
2,000,000	6,500	300,000	Desert Peak (BLM 2003)
Average estimated consumption		180,000	

- *Lithostratigraphy* of injection/production boreholes and wells,
- Geology and geochemistry of the host geothermal reservoir,
- Presence/absence of intrinsic fractures, and
- Stress regime.

A review of the literature reveals a wide range of water volumes used to stimulate wells associated with a given project. Table 5 summarizes volumes used for water-based stimulation activities from the literature, organized by the type of geologic formation stimulated (see Appendix B for a more detailed table). For the literature reviewed, hydraulic and chemical stimulation and not thermal stimulation are relied upon for stimulation of geothermal reservoirs. However, it is likely that thermal stimulation contributes as a secondary factor during hydraulic stimulation due to the temperature difference between the reservoir temperature and the injectate temperature. For the EGS sites reviewed, water requirements varied by three orders of magnitude from 100 m^3 (26,400 gal) for a single stimulation at a well in Bad Urach, Germany, to

TABLE 5 Summary of Water-Based Stimulation Activities from the Literature

Geologic Formation Stimulated	Volume of Water (m^3)	References
Andesite	13,000	Zimmermann et al. 2009
Gneiss	100	Stober 2011[a]
Granite	24,000[b]	Asanuma et al. 2005 INL 2006 Häring et al. 2008[a] Chen and Wyborn 2009 Evans et al. 2012 Portier et al. 2009 Xu et al. 2012 Michelet and Toksöz 2007 Cordon and Driscoll 2008 Schindler et al. 2010
Granodiorite	5,800[c]	Kitano et al. 2000
Metasediment and felsic porphry dolerite dykes	2,700	Beach Energy et al. 2010
Paragneisses and metabasites	30,000[d]	Shapiro et al. 2006 [a] Zoback and Harjes 1997
Volcanic rock	91,000	Cladhous et al. 2012

[a] As referenced in McClure and Horne (2012).
[b] Stimulation volume represents an average from the projects cited.
[c] Stimulation volume represents an average from multiple stimulation events of two different wells.
[d] Stimulation volume represents an average from multiple stimulation events of a single well

91,000 m^3 (24,000,000 gal) for a multizone well stimulation at Newberry Volcano (Stober 2001 as referenced in McClure and Horne 2012; Cladouhos et al. 2012). For the majority of the sites reviewed, water alone was used as a stimulation fluid. At some sites, water, water and sand, and, in the case of international EGS projects, water/proppant/gel mixtures were used. At several sites, chemical stimulation methods were used. Chemical stimulation fluids included regular mud acid (RMA), acid solutions, basic solutions, and chelating agents.

Well stimulation methods have a long and successful history with the petroleum industry. Similar techniques have been used to economically access both petroleum and EGS reservoirs. EGS reservoirs are often situated in crystalline igneous geologic formations with low porosity and permeability, which results in a poor hydraulic connection between the host formation and

installed wells such as is the case at Soultz-sous-Forêts, France; Desert Peak, Utah; and Groβ Schönebeck, Germany (Portier et al. 2009; Chabora et al. 2012; Zimmermann and Reinicke 2010). In some cases, poor connectivity between wells and the host formation can also result from the well installation method. Intrinsically low permeability and low porosity can result in an impaired ability to harness the heat stored in the formation. In most cases, the success of an EGS project depends upon dilating existing fractures, creating new fractures, and keeping existing and newly created fractures open (Portier et al. 2009).

The applicability of each type of stimulation depends on the reservoir-well environment, which is the structural geologic setting, and includes the nature of the reservoir rock, the way the boring and well were developed, and the stratigraphic sequence of the targeted well(s). With key reservoir parameters and well-specific characteristics in mind, practitioners might use any one or all three of the stimulation methods either singly or in sequence (Zimmermann et al. 2011).

3.2.1 Thermal Stimulation

Thermal stimulation involves pumping cold water, typically at pressures not likely to create fractures, into either a production or injection well. Thermal stimulation has been used in both volcanic and metamorphic geothermal reservoirs to enhance the productivity of wells (Zimmermann et al. 2011).

For geothermal wells, in general, the duration of thermal stimulation operations can range from a few hours to a few days. Thermally induced contraction of the host formation can cause the dilation of existing fractures. Since withdrawal of the cold stress can cause the dilated fractures to close, thermally induced stimulation is often performed on the cooler injection wells rather than on the warmer production wells (Grant and Garg 2012). However, there is a possibility that cracking or spalling caused by the thermal stress from cooling creates in situ proppants that preserve the dilated fractures once the cold stress is removed, which suggests that thermal stimulation could be used on both production and injection wells (Axelsson et al. 2006; Grant and Garg 2012).

For thermal stimulation (and hydraulic and chemical stimulation for that matter), inflatable mechanical devices known as "*packers*" can be used to isolate and target specific intervals for treatment. Some researchers have noted that the conditions in geothermal wells preclude their use since mechanical packers may not be compatible with high temperatures (Grant and Garg. 2012). However, both single and double open-hole packers have been deployed for thermal stimulation efforts in what are termed "low temperature" geothermal wells in basaltic rock in Iceland (Axelsson et al. 2006).

The functionality of packers can also be mimicked by using mixtures of chemical or biological constituents to isolate discrete portions of a boring for stimulation. These chemical or biological constituent-based preparations can be referred to as "bridges" or "diverters." Bridges or diverters can be designed and emplaced to isolate one fracture interval while another interval is being stimulated. After the stimulation is complete, heat degrades the diverter, and dissolution opens up all of the fractures that were stimulated (Zimmermann et al. 2009; BLM 2011i).

Examples of thermal stimulation include the DOE EGS Demonstration Projects located in Northwest Geysers, California, and Newberry Volcano, Oregon. At the Northwest Geysers site, the intent of the EGS Demonstration is to show that the permeability of a high-temperature reservoir can be thermally stimulated by fracture reactivation. Two of the previously abandoned wells have been reopened and deepened as an EGS couplet. One of the wells, P-32, is being stimulated using "cool" injection water (Garcia et al. 2012). At the Newberry site, investigators targeted intrusive contacts located 2,829 to 2,924 m (9,280 to 9,560 ft) below ground surface for thermal stimulation using cool water (10°C [50°F]) produced from an onsite water well (Cladouhos et al. 2012). Another example of thermal stimulation involves the introduction of water through the drillstring, a combination of the drillpipe and bottomhole assembly that is used to turn the drillbit. A common technique used for high-temperature well stimulation in Iceland is the intermittent injection of cold water with periods of thermal recovery in between the injection episodes (Axelsson et al. 2006).

3.2.2 Hydraulic Stimulation

Hydraulic stimulation involves the introduction of fluids into subsurface rocks under sufficient pressure to (1) open or extend existing fractures or (2) create new fractures, thus expanding the volumetric extent of a given geothermal reservoir. Some authors have estimated that for each net MW of power, about 28 million m^3 (1 billion ft^3) of reservoir are required, while others have estimated that the minimum rock volume required to sustain production from a granite formation is about a cubic kilometer (35 billion ft^3) (Sanyal et al. 2007; Richards et al. 1994). Hydraulic stimulation is one method that can be used to impact thermal reservoirs at such an expansive volumetric scale.

Two general types of hydraulic stimulation are used in EGS activities—*hydraulic shear stimulation* and *hydraulic fracture stimulation*. Shear stimulation injects fluid at low pressures such that the least horizontal principal stress (S_{hmin}) is not exceeded (Chabora et al. 2012). The lower pressure ensures that the propagation of shear displacement occurs along the existing fracture plane, and may or may not result in the self-propping dilatation of the created fracture. In contrast, hydraulic fracture stimulation, or *hydraulic fracturing*, requires fluid to be injected at pressures above S_{hmin}, also known as the fracture initiation pressure, to create new fractures in the reservoir (Chabora et al. 2012).

Hydraulic stimulation can involve the use of water ("waterfrac"), gel-proppant fracs, or a combination of both fluids known as "hybrid fracs." EGS geothermal reservoirs in the United States, which are all located in igneous formations, have been stimulated with waterfracs. Outside of the United States, EGS geothermal reservoirs have been stimulated with waterfracs, while gel-proppant fracs have been used to stimulate geothermal reservoirs in both sedimentary rock (at Groß Schönebeck, Germany) and igneous rock (Bad Urach Germany, and Fjallbacka, Sweden) (Zimmermann and Reinicke 2010; INL 2006). Fluids can be introduced via a single high pressure and high flow rate injection event by gradually increasing pressure and flow over the period of the stimulation, or by cyclic episodes of high pressure and high flow injection interspersed with periods of low pressure and low flow or no injection (Karner 2005;

Zimmermann and Reinicke 2010; Chen and Wyborn 2009; Chabora et al. 2012; McClure and Horne 2012).

Reservoir engineers tend to select the fluid type used for stimulation and the injection pressure used to introduce the fluid into the reservoir formation based upon the nature of the geologic formation; including both the rock type (sedimentary, igneous, or metamorphic), the presence and orientation of natural or intrinsic fractures, and the natural tendency for fracture propagation when stimulated. Hydraulic stimulation can proceed as a campaign involving the strategically planned injection of different fluids at different injection pressures applied at single or multiple intervals in either injection or production wells (Zimmermann et al. 2009; Zimmermann and Reinicke 2010; Chabora et al. 2012). Three hydraulic well stimulation field tests are discussed below by way of illustration.

3.2.2.1 Desert Peak, Nevada

At the Desert Peak site, researchers applied stimulation techniques in an attempt to commercialize unproductive wells in an existing geothermal field. The goals for the project were to increase the permeability and injectivity of well 27-15 to commercial levels, to improve hydraulic connection to the producing geothermal field, and to demonstrate the potential for enhanced power generation through successful stimulation.

A multiphase stimulation plan involving several phases of low-pressure (below minimum horizontal stress) shear stimulation, two phases of chemical stimulation, and a hydraulic fracturing phase was implemented. Each phase of the plan was linked to a pre-approved decision tree that allowed the project team to proceed with the stimulation plan based upon the outcomes of each phase. The primary benchmark used to progress through the decision tree was whether or not well 27-15 reached commercially acceptable targets for an injection well in the Desert Peak geothermal field. After just the 113-day shear stimulation phase, the injection rate increased an order of magnitude from a few gpm to 10s of gpm (Chabora et al. 2012).

3.2.2.2 Groß Schönebeck, Germany

A hydraulic shear stimulation experiment performed to enhance a geothermal research well at Groß Schönebeck, Germany, involved two different stimulation fluids. The volcanic formation present at the bottom 20 m (66 ft) of perforated casing in well GtGrSk4/05, 3,900-m (12,800-ft) measured depth, was first isolated by what is termed a "*bridge plug*" and then stimulated by a waterfrac and quartz sand treatment. Several high flow and high pressure injection intervals at 50 L/s (793 gpm) and 58 MPa (8,412 psi) followed by low flow and low pressure injection intervals at 20 L/s (317 gpm) and 45 MPa (6,527 psi) of short duration were used with the goal of achieving a predicted fracture zone with a total fracture volume of 100 to 200 m^3 (3,500 to 7,000 ft^3). Alternating periods of high and low flow rates were used to control the direction of fracture propagation and to conserve water (Zimmermann and Reinicke 2010).

On the basis of borehole measurements, a discrete portion of the Lower Dethlingen sandstone layer overlying the volcanics was then isolated with a bridge plug and targeted for stimulation. Since sandstone has limited susceptibility to water-based stimulation because of leak-off into the permeable matrix, a hydraulic gel–proppant fluid consisting of a highly viscous gel and specially designed and selected artificial ceramics (proppants) was used to create and maintain fracture conductivity in the sandstone formation. The casing above the volcanic layer was perforated (20 circumferential, 15-mm [0.6-in.] diameter shots per meter), and the targeted interval was subject to a gel-proppant treatment. Reservoir engineers performed a leak-off test, a step-rate test, and then performed the regular stimulation treatment. A total of 95 metric tonnes (105 tons) of high-strength proppant was injected. Coated and noncoated high-strength proppants were used. The 24 metric tonnes (26 tons) of coated proppants was used to create a barrier near the well to prevent noncoated proppants from flowing back into the well (Zimmermann and Reinicke 2010).

3.2.2.3 Cooper Basin, Australia

During the proof of concept program used to evaluate the economic extraction of heat from a nonvolcanic granitic basement in the Cooper Basin, Australia, reservoir engineers performed four large-scale hydraulic stimulations in three wells—Habanero #1, 2, and 3. The water-based stimulations were carried out by injecting "fresh water," which in this case is composed of river water, shallow groundwater, and some recycled brine, at 67 MPa (9,700 psi) at different depth intervals resulting in new fractures or the extension of existing fractures in some cases. Fresh water injected into the Habanero wells resulted in the creation of subhorizontal fractures in Habanero #1 and #2, the extension of an original fracture zone in Habanero #1, and improved productivity at Habanero #3 (Chen and Wyborn 2009).

3.2.3 Chemical Stimulation

Chemical stimulation typically involves the introduction of acid with a goal of mobilizing and removing acid soluble materials from the boring/well face or from fractures in close proximity to the well. A partial list of chemicals used in chemical stimulation is provided in Appendix C. To a large extent, chemical stimulation techniques used on geothermal wells have been borrowed from the oil and gas industry. There are two types of chemical stimulation operations in the oil and gas industry: *matrix acidizing* and *fracture acidizing*. In matrix acidizing, the acidic stimulation fluid is injected at a low enough pressure to prevent fracturing. In the case of fracture acidizing, the technique involves injecting an acid fluid into the formation at sufficient pressure to cause a wellbore pressure buildup, which results in an increase in fracture length and width (Portier et al. 2009).

In the case of geothermal wells for EGS, several types of chemical stimulation have been used. At the Groß Schönebeck site, the Dethlingen sandstone formation has been treated with a matrix acidizing compound (Zimmermann and Reinicke 2010). At the Fenton Hill site, sodium carbonate (Na_2CO_3) was used to treat a single well (McClure and Horne 2012). At the Soultz-sous-Forêts site, hydraulic stimulation efforts were followed up with chemical stimulations on

three wells in response to seismicity concerns (Portier et al. 2009). Wells GPK 2, GPK 3, and GPK 4 were stimulated by using hydrochloric acid (HCl) in an effort to dissolve carbonates that may have deposited in the reservoir fractures. Well GPK 4 was also stimulated by using RMA and in a separate chemical stimulation by using a thermally stable chelating agent. Wells GPK 4 and GPK 3 were also treated with a retardant chemical product referred to as "organic clay for high temperature" (OCA-HT), which consisted of a mixture of citric, hydrofluoric, and borofluoric acid and ammonium chloride. OCA-HT can penetrate into a formation and combines an acidizing effect with a chelating effect to address calcite and silicates and is recommended for use in elevated temperatures (Portier et al. 2009). Table 6 presents a summary of projects that use chemical stimulation, including volume of fluid for chemical stimulation.

3.3 WATER REQUIREMENTS FOR FLOW TESTING AND CIRCULATION TESTING

In addition to stimulating an EGS reservoir, several tests must take place to verify enhancement and circulation. Each of these tests requires the addition of water. These include pre-stimulation and post-stimulation tests for an individual well, a short-term circulation test once a doublet or triplet production and injection well system have been installed, and a long-term circulation test once the series of doublets or triplets has been installed at commercial scale. Table 7 shows typical water volumes, flow rates, and lengths of time for these steps. Although consumption estimates assume that no water is reused, it may be possible for water recovered from one test to be used for another test. The estimates for long-term circulation have yet to be verified with commercial-scale EGS development (INL 2006).

3.4 ABOVEGROUND OPERATIONAL WATER CONSUMPTION

In the previous report of this series, operational water consumption was determined to be the greatest contributor to water consumption over the life cycle for all geothermal technologies (Clark et al. 2011). These estimates for consumption, however, were based upon limited production and injection data. For the current analysis, operational water usage data for geothermal power facilities were collected and analyzed in three ways. First, additional production and injection data were obtained and analyzed from geothermal facilities in Nevada. Next, water permits for geothermal power plants from the State of Nevada were reviewed. Finally, operational water consumption data from NEPA documents and other literature were aggregated.

TABLE 6 Chemical Stimulation Projects Found in the Literature

Location	Well Name	Stimulation Media	Volume (m^3)	Geologic Formation Stimulated	Reference
Desert Peak, Nevada	Well 27-15	2% SPA	136	Rhyolite	Chabora et al. 2012
Desert Peak, Nevada	Well 27-15	Water	83	Rhyolite	Chabora et al. 2012
Desert Peak, Nevada	Well 27-15	12%/3% HCl/HF	49	Rhyolite	Chabora et al. 2012
Desert Peak, Nevada	Well 27-15	Water	76	Rhyolite	Chabora et al. 2012
Soultz-sous-Forêts, France	GPK 2	2 steps 0.09% HCl and 0.18% HCl	1,360	Granite	Portier et al. 2009
Soultz-sous-Forêts, France	GPK 3	865 acid solution then 7,000 water	7,865	Granite	Portier et al. 2009
Soultz-sous-Forêts, France	GPK 4	Acid solution	4,700	Granite	Portier et al. 2009
Soultz-sous-Forêts, France	GPK 4	Water, RMA, water	4,225	Granite	Portier et al. 2009
Soultz-sous-Forêts, France	GPK 4	Water, caustic + NTA, water	5,200	Granite	Portier et al. 2009
Soultz-sous-Forêts, France	GPK 3	Water, OCA, water	2,850	Granite	Portier et al. 2009
Soultz-sous-Forêts, France	GPK 4	Water, OCA, water	1,150	Granite	Portier et al. 2009
Groβ Schönebeck, Germany	GtGrSk4/05	7.5% HCl	10	Sandstone	Zimmermann and Reinicke 2010
Landau, Germany	GtLa2	33% HCl	95	Granite	Schindler et al. 2010

Abbreviations: HF = hydrofluoric acid; HCl = hydrochloric acid; NTA = nitrilotriacetic acid; OCA = organic clay acid; RMA = regular mud acid; SPA = sodium sulfophthalate.

TABLE 7 Flow Test and Circulation Test Water Requirements for EGS

Step	Flow Rate (kg/s)	Volume (m^3)[a]	Length of Time (days)	Source
Pre-stimulation test	5–7	400–600	1	INL 2006
(per stimulated well)	9	2,300	3	Morris 1980
Post-stimulation test	7–50	7,200	2.5	INL 2006
(per stimulated well)	8	400	0.5	Zimmermann and Reinicke 2010
	4	2,000	6.3	Morris 1980
	13	300	0.3	Morris 1980
Short-term circulation	20	2,600–3,600	21	INL 2006
(applied per doublet well)	4	2,500	7	Kitano et al. 2000
	8	6,500	9	Kitano et al. 2000
	14	4,000–9,000	24	Chen and Wyborn 2009
	17–34	31,500 (44,500)	30	INL 2006
	17–34	25,500 (51,500)	25	INL 2006
Long-term circulation (applied per doublet well)	50–100	4,000–13,000	21	INL 2006

[a] Values in parentheses represent total volume used, not consumed.

To complement analysis conducted previously by Argonne for geothermal facilities in California, production and injection data for Nevada geothermal plants were obtained from the Nevada Division of Minerals (http://www.nbmg.unr.edu/lists/Production/index.html) for 19 facilities across the state:

- Beowawe;
- Blue Mountain Faulkner
- Brady Hot Springs;
- Desert Peak 1 and Desert Peak 2;
- Dixie Valley;
- Empire San Emidio;
- Galena 2 and Galena 3;
- Moana;
- Richard Burdette (Galena 1);
- Salt Wells;
- Soda Lake;
- Steamboat 1/1A, Steamboat II, and Steamboat III;
- Steamboat Hills;
- Stillwater; and
- Wabuska.

These data are self-reported by the facility's operator on a monthly basis for each production and injection well utilized by the plant. The report specifies, at a minimum, the gallons of geothermal fluid produced or injected for each well, as well as the temperature of that fluid. By using these two data points, it was possible to do a mass balance conversion and derive the pounds of water produced/injected per month. By comparing production and injection data within 1 month, makeup and/or loss rates were estimated for each facility. Further calculations included annual loss/makeup in gallons per year and average annual loss/makeup per megawatt-hour equivalent.

While this was done for all facilities listed, the production/injection datasets were not all useful for several reasons. The most prevalent were that production/injection data were inadequately reported or the facility was too recently constructed. In these cases, because of a lack of data, a robust trend was unavailable. Because of this, only datasets with a minimum of three continuous full years of production/injection data were chosen for further analysis (Blue Mountain, Moana, San Emidio, and Saltwells were excluded). In addition, data from the multiple facilities in the Steamboat Complex (Steamboat 1/1A, II, III, Steamboat Hills, Richard Burdette, Galena 2, and Galena 3) were combined because some of the facilities shared injection wells. The remaining data were combined with data from four plants in California; these data are summarized in Appendix D, Table D-1. Production and injection data from Coso that were previously reported have not been included in this report because of uncertainty over the completeness of the reported data. Further analysis indicated that the data for this site may be incomplete; that is, the data include only production and injection wells on BLM land and exclude data from wells on Navy property.

Recent discussions with state officials and industry representatives have called into question the precision and value of the production and injection data for determining fresh water consumption from geothermal power plants. Often the data are reported based upon single monthly point measurements of flow rates and temperatures rather than monthly averages which can introduce monthly variability into the data. There is also the potential for error in converting volume flows to mass flows. Since total dissolved solids (TDS) are not reported, they had to be estimated and were assumed to be constant (between production and injection) when performing the required density corrections. Furthermore, failure and calibration issues with flow meters have been suspected as a common issue with the reported production and injection data. An effort was made to exclude any data points that appeared to be anomalies from the averages, but some measurement error still likely remains within the datasets. Two air-cooled binary power plants within the data set show a difference of approximately 2% between the production and injection volumes calculated by this method, despite the fact that these systems operate in a closed-loop manner and should exhibit no loss of geofluid. This should give a reasonable approximation of the level of error expected in the use of these data.

While the production and injection data are unlikely to be useful for quantifying water consumption for air-cooled, hybrid-cooled, or wet-cooled binary systems (that use outside water sources), it may be useful for estimating geofluid losses from wet-cooled flash systems. Unlike other system designs, wet-cooled flash systems typically exhibit large and relatively consistent differences between production and injection over time, which should be easier to resolve despite the small errors in the underlying data. Given that the error in the underlying data appears to be

on the order of 2% of flow, and the differences between production and injection for most wet-cooled flash systems appear to be on the order of 20%, this method should still give a reasonable approximation of the geofluid loss for these systems. When normalized for electricity production, the average geofluid loss for the four wet-cooled flash systems in Table D-1 is 2.4 gal/kWh. This matches well with the previous Argonne estimate of 2.7 gal/kWh for the flash scenario modeled in GETEM (Clark et al. 2011).

An extensive review of all applicable water permits issued by the State of Nevada for geothermal facilities was conducted through the Nevada Division of Water Resources Permit Search web portal (http://water.nv.gov/data/permit/index.cfm). A database was constructed to link permits with their geothermal facility. This was done in an attempt to compare permitted water usage with makeup and loss rates from the self-reported datasets mentioned above.

Two types of permits were issued for geothermal power plants in Nevada for geofluid extraction and fresh water consumption. Permits were issued for the extraction of geofluid, typically with some specification of permissible fluid losses (fluid not reinjected). Where available, the permitted production and loss values for each facility are presented next to the reported production and injection data in Appendix D, Table D-1. In all cases, the reported flows were less than the permitted flows, which indicates that all power plants were in compliance with their permits. In most cases, the losses reported were significantly lower than those permitted by the state, although the losses reported at Beowawe were nearly identical to those permitted.

The other permits issued by the state were for fresh water consumption from either ground or surface water. These permits were of most interest in terms of estimating operational water consumption. Such permits were identified for Dixie Valley, San Emidio, Soda Lake, and the Steamboat Complex. Dixie Valley included separate permits for drilling and operational needs and for a reservoir augmentation injection program. The San Emidio permits specified consumptive use for cooling water. The Soda Lake permits specified for cooling water, dust suppression, and maintenance. The water from the Steamboat Complex permits is primarily being used to test hybrid cooling solutions. Data from these permits are combined with data from the literature review and are presented in Figure 2 and in Appendix D.

The document review was used to collect additional operational water usage data from NEPA documentation, such as EAs, EISs, and other relevant documentation (see Section 3.2 for more information on this analysis). In all, operational water data from 16 facilities were collected; 13 in the United States, 1 in Australia, and 2 modeled theoretical systems. The data from this analysis plus the data from the Nevada water permits are presented in Figure 2 and in Appendix D.

The data are presented by cooling system type; different symbols indicate the power plant type for each data point. Note that a few data points were from sources where there was either a mix of binary and flash plants aggregated together at the same site, or where water consumption was projected for a plant that had not yet been built and there was uncertainty about whether the plant would utilize a binary or flash system. Wet-cooled flash plants ranged from 0.7 to

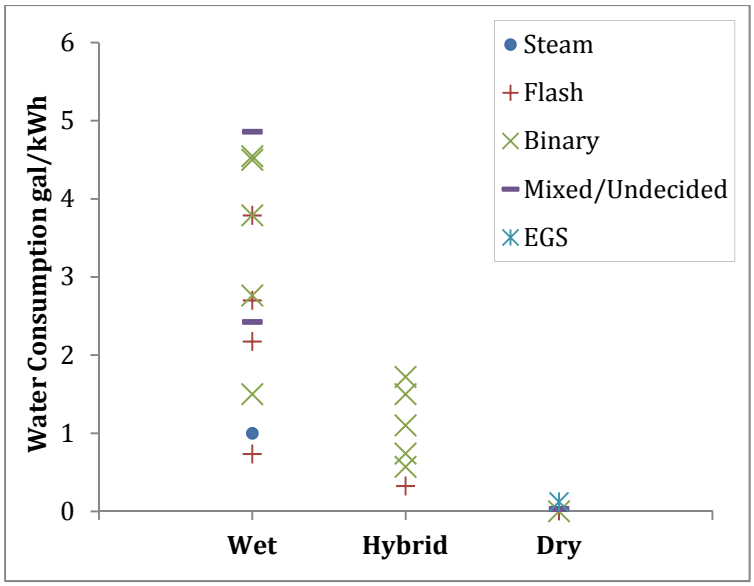

FIGURE 2 Geothermal Operational Water Consumption Data

3.8 gal/kWh, with an average of 2.4 gal/kWh. Water consumption from wet-cooled binary plants was slightly higher, ranging from 1.5 to 4.6 gal/kWh, with an average of 3.4 gal/kWh. This difference is likely attributed to two factors: (1) flash plants operate with higher temperature geofluid, which makes them more thermodynamically efficient, and (2) many of the data points for flash systems were based upon injection augmentation programs, which may not account for 100% replacement of lost geofluid. Injection of makeup water into a geothermal reservoir to replace evaporated geofluid condensate used for cooling in flash plants is optional and does not occur at many flash plants. This is an operational decision that is based upon economics and the local availability of water. Injection can extend the life of the reservoir at the cost of significant water consumption. When supplemental injection is not practiced, non-geofluid operational water consumption is minimal and similar to that of dry-cooled systems. In contrast, binary plants are almost always operated as closed-loop systems with all of the produced geofluid being directly reinjected, and they always require an external source of high-quality water for cooling if a wet- or hybrid-cooling system is used.

Hybrid cooling systems combine air and wet cooling and rely on air cooling most of the year, but supplement with wet cooling in warmer weather. Hybrid cooling systems can increase the power output of a geothermal power plant in the summer when power prices are highest, while requiring significantly less water than a wet-cooled system. There are many different designs of hybrid cooling systems, and the decision on when to operate them is ultimately an economic one: trading off the cost and impact of water consumption versus the incremental increase in power production revenue depending upon the ambient conditions. Referring again to Figure 2, water consumption for hybrid cooling systems ranged from 0.3 to 1.7 gal/kWh. The average was 1.0 gal/kWh.

As shown in Figure 2, the operational water consumption for dry-cooled systems is quite low compared to wet- and hybrid-cooled systems. There is no direct water consumption for dry cooling; however, there can be water consumption for other operational activities, including dust suppression, maintenance, and domestic needs. All data obtained for noncooling-related operational water consumption from all systems were used to estimate the operational water consumption from dry-cooled systems. The data ranged from 0.001 to 0.12 gal/kWh. The average was 0.04 gal/kWh.

While these data represent the best collection of operational water consumption from geothermal power plants that currently exists, some important caveats must be made. The production and injection data reported to the states are imprecise and only useful for roughly approximating geofluid losses from wet-cooled flash systems. The data from state water permits indicate how much water a geothermal power plant is allowed to use, but it does not indicate how much a plant is actually using and, therefore, should be viewed as a maximum value for that specific plant. Also, because of the nature of the NEPA process, much of the NEPA documentation collected was prospective; that is, because the analysis has to be conducted before the construction of the facility, it assumed certain kinds of configurations, levels of production, cooling technologies, etc. In some cases, this may be how the facility actually turns out. However, in other instances, there could be changes to these approaches later on. The ultimate goal would be to obtain direct operational water consumption from operating geothermal power plants. Unfortunately, reporting these data for existing geothermal power plants in the United States is not required by any state or federal authority, nor are they voluntarily reported.

3.5 BELOWGROUND OPERATIONAL WATER LOSSES

EGSs are unique from other geothermal systems in that they rely on artificially created reservoirs in formations that may not have sufficient fluid in place or permeability to economically generate power. Fluid, most often water (but may be CO_2 in some EGS systems), must be added to the reservoir and circulated between injection and production wells to generate power. The geothermal reservoir that is created is rarely completely sealed, and, over time, some portion of the introduced fluid is often "lost" to the surroundings. These losses must be made up by introducing additional fluid to maintain reservoir pressures, flow rates from production wells, and power output.

Operational loss belowground refers to fluid injected into the reservoir and not returned to the surface during steady-state operations. These losses are commonly calculated as the difference between average injection and production rates over a given period of steady-state operation. There are three mechanisms by which this fluid is lost, though this loss may not be permanent; depending on the mechanism of loss, it may return to the surface upon depressurization of the reservoir. Fluid may be permanently lost either by (1) pressure diffusion on the periphery of the reservoir or by (2) leakage through natural faults and fractures extending beyond the reservoir. Fluid loss can also occur through (3) expansion of the engineered reservoir—either through new fractures within the reservoir periphery or dilation of existing ones. Upon depressurization of the reservoir, some of the fracture dilation may be lost, and thus the operational fluid filling this space will return to the surface (Murphy et al. 1999).

Since few EGS projects have been implemented, data on belowground operational loss rates are sparse. The data that exist vary widely. Table 8 presents reservoir loss percentages from the literature. Descriptions and reservoir loss percentages sometimes differed among sources for the same sites; thus these data are presented with their sources in the table. Because the test EGS project at Fenton Hill is one of a few to have run multiple circulation tests over a period of years, more data exist for it than for any other site. Only EGS projects where data on belowground operational losses were found are included in Table 8; thus several well-known projects are not listed there, including the EGS project at Landau.

Several test projects have resulted in loss rates that are too high for the project to be viable. Circulation tests at Rosemanowes, England, resulted in loss rates as high as 75% (Richards et al. 1994). The lowest rate recorded at the site was 20% (McClure and Horne 2012; Evans et al. 2012). The test site at Hijiori, Japan, showed losses between 30 and 70% (Matsunaga et al. 1995; Murphy et al. 1999), and injections at Fjallbacka, Sweden, resulted in 50% loss (Evans et al. 2012). Mishra et al. (2010) claim that belowground operational fluid loss should be below 10% for an EGS project to be viable in the long term.

Other, more viable, sites show lower loss rates. Fenton Hill, New Mexico, has shown loss rates to be about 10% (Murphy et al. 1985, 1999; Duchane and Brown 2005), with several sources claiming that eventual steady-state losses will approach 1% (Farison 2010; Mishra et al. 2010). Belowground operational losses at the proposed EGS project at Newberry Volcano are expected to be 10% (Stroud et al. 2011). Sources for the Soultz site give loss percentages of 2% and lower (Evans et al. 2012).

Though the data on belowground operational loss are limited, several characteristics of loss rates are clear from the literature: belowground operational loss is heavily dependent both on local geologic characteristics and on surface injection or reservoir pressure (while these two pressures are different, they are correlated). Differences in geology largely explain why some sites, like Hijiori, have such high loss percentages while other sites, like Fenton Hill, have more manageable losses. Belowground operational loss can even vary highly among wells on a single site, as exemplified by Rosemanowes. The well drilled to a depth of 2.0 km (1.2 mi) suffered much higher loss rates than one drilled to 2.6 km (1.6 mi) not very far away (Richards et al. 1994).

The two sites for which data on injections at different pressures were obtained (Rosemanowes and Hijiori) exhibited a positive correlation between injection pressure and belowground operational loss (Murphy et al. 1999; Richards et al. 1994). The effects of pressure increase on loss were significant: at Rosemanowes, increasing the injection pressure from 4–11.8 MPa (600 to 1,710 psi) expanded the loss rate from 20 to 45% (1,710 psi [11.8 MPa] is near the fracturing pressure of the reservoir formation). At Hijiori, an increase in pressure from 8–12 MPa (1,000 to 1,700 psi) expanded loss from 50 to 70%. Indeed, injection pressure is identified by INL (2006) as a major determinant of loss, because high injection pressures extend fractures and increase permeability beyond the reservoir, thus allowing fluid to escape. Also, higher pressures can dilate existing fractures within the reservoir and cause it to store more water (which appears as an operational loss when the dilation occurs). This relationship illustrates a

TABLE 8 EGS Operational Losses Belowground[a]

Site	Source	Makeup	Well Depth (km)	Wellhead Injection Pressure (MPa)	Loss Percentage (%)	Notes
Fenton Hill	Murphy et al. 1985	Biotite granodiorite (hard crystalline rock)	2.9		10	
	Duchane and Brown 2005	Highly jointed Precambrian plutonic and metamorphic complex	4		12	After continuous flow period of 3.5 months and continuous pressurization period of 6 months
					7	After continuous flow period of 1.5 months and continuous pressurization period of 15 months
					14	After continuous flow period of 6 months and continuous pressurization period of 2 months
	Murphy et al. 1999				10	
	Farison 2010				1	Loss percentage represents system after long-term circulation
	Mishra et al. 2010				5	Reported as long-term loss sourced from Murphy et al. 1985 (unclear how this number is drawn from the source)
					1–2	Reported to be sourced from Duchane 1996 (unclear how this number is drawn from the source)
Fjallbacka	Evans et al. 2012	Granite, near critical stress	0.5		50	
Hijiori	Murphy et al. 1999			8	50	
				12	70	
	Matsunaga et al. 1995		1.9–2.2		30	
Newberry Volcano	Stroud et al. 2011				10	Anticipated (not measured)

TABLE 8 (Cont.)

Site	Source	Makeup	Well Depth (km)	Wellhead Injection Pressure (MPa)	Loss Percentage (%)	Notes
Rosemanowes	Richards et al. 1994		2		70–75	
			2.6	4	20	
				11.8	45	
					35	Mean value of tests
	McClure and Horne 2012				20	
	Evans et al. 2012	Carnmenellis granite	2.65		20	Average fluid losses of circulation tests from August 1985 to the end of 1989
Soultz	Evans et al. 2012	Granitic, horst-and-graben structure, critically stressed	3.5		0	Reported as "injection equals production" and "did not involve a component of net injection"
	Mishra et al. 2010				1–2	
General	DeMeo and Galdo 1997				5–15	Acknowledges higher rates are possible, but possibly uneconomic
	INL 2006				2	Assumption for scenario

[a] Because data on reservoir makeup, well depth, and wellhead injection pressure varied among sources and different tests within sources, they are listed for individual sources and tests (individual loss percentages) and not overall for each site. These fields are left blank when the source of the loss percentage did not include values for the particular site or test.

significant tradeoff in EGS production. While increasing pressure increases flow rate, it also results in greater operational loss belowground.

The data also show that pressure is a much more influential determinant of belowground operational loss than is flow rate. It could reasonably be expected that for losses from pressure diffusion, longer periods of higher flows might saturate the formation surrounding the reservoir, thus blocking flow and reducing losses. Murphy et al. (1999), however, claim that losses from pressure diffusion are not dependent on flow rate but on pressure and time. Furthermore, the Fenton Hill data from Duchane and Brown (2005; displayed in Table 8) show that for overall loss, including all three mechanisms, pressure history has a much larger impact than flow rate. As explained in Duchane (1996), pressure was maintained in the reservoir between the first test (that resulted in a fluid loss of 12%) and the second test (that resulted in a loss of 7%), but flow was dramatically reduced. In contrast, the pressure was allowed to decline between the second and third tests, and the third test resulted in a higher fluid loss (14%) despite having a much longer period of continuous flow prior to the test than did either of the two previous tests. Extended periods of maintained pressure serve to reduce losses from a reservoir over time. It should be noted, however, that this relationship does not suggest that higher pressures reduce loss versus lower pressures (as that would contradict a characteristic of belowground operational loss described above), but rather that maintaining a given pressure over time tends to reduce loss at that pressure level—whereas maintaining flow has much less of an impact on loss, if any.

3.6 SOURCE WATER FOR DRILLING, STIMULATION, AND OPERATION ACTIVITIES

The Project Database was used to determine the source of water for a variety of geothermal activities, such as well drilling, stimulation, and power plant operations. The database was analyzed for instances where water source was mentioned, and these instances were compiled into a second database, which organized the information by project name, project location, type of operation, and water source. This database was then analyzed using two key assumptions. First, if an activity listed multiple sources of water for one operation, all of them were included. For example, the Geysers project in California listed several sources of stimulation water, such as treated wastewater, stormwater, and surface water. It was also not uncommon for geothermal power plants to list several sources of operational water that may be needed when energy demand increases in summer months. In addition, for the purposes of this analysis, cooling water and makeup water were grouped together as "operational" water. The analysis reviewed a total of 36 projects, which included geothermal projects in various stages of the NEPA review process, including exploration, drilling or development, and production or utilization.

For the purposes of this analysis, *groundwater* is defined as water that is derived from aquifers and other sources belowground. While geofluid is technically groundwater, it is normally hydrologically distinct from groundwater sources, not of sufficient quality to be potable due to high salinity and TDS concentration, and is typically much warmer than normal groundwater sources. Finally, the two sources are often permitted differently at the state level.

Surface water is defined as water that is available aboveground in a stream, lake, or river and that can be obtained without drilling a well. *Condensate* is defined as water that has passed through the cooling system of a flash geothermal power plant. *Stormwater* is defined as atmospheric water that falls to the earth as precipitation and is then collected on the earth's surface. Finally, *treated wastewater* is defined as municipal sewage/effluent that is treated at a publicly owned treatment works (POTW) before being discharged.

It is also worth noting that for several geothermal power plants in the Salton Sea area of California, although groundwater may be listed as a source of water, the aquifers in that area are, in fact, often supplemented by water from surface sources due to overpumping of groundwater in the area. That is, surface water is often reinjected into these aquifers before it is later withdrawn as groundwater. For the purposes of this analysis, the water source for these projects was listed as surface water, not groundwater, as it mainly comes from the Colorado River via the Imperial Irrigation District (IID) or the Coachella Irrigation District (CID). The project sites where this occurs include Truckhaven, West Chocolate Mountains, and Ormesa. In several instances, the NEPA documentation for the project listed both sources (IID and CID) as water sources as a decision had not yet been made as to which district would supply the water.

The results of this analysis found that for drilling, approximately 83.3% of the 23 geothermal projects analyzed that included a drilling component used groundwater as their primary source of drilling water (Figure 3). In addition, 8.3% used surface water as a source, one project utilized geofluid, and one project used condensate from an existing power plant as a source for drilling water. The same project also used both geofluid and condensate for drilling water, leading to 24 total data points for this operation.

For geothermal well stimulation of EGSs, the results were more varied (Figure 4). Of the eight projects that provided source water information in their documentation, there were five instances of groundwater being used as a source of stimulation water, or 50% of the time. There were two instances of surface water being used as a water source (20%), and then one instance each of treated wastewater (10%), condensate (10%), and stormwater (10%) being used. As can be seen from this analysis, there were 10 data points for 8 projects. As was stated previously, this is the result of some projects using multiple sources of water for stimulation.

Finally, for operational water usage, of the 16 projects that provided data in this area, there were 12 instances of groundwater being used, representing almost half, or 48%. There were six instances of surface water (24%), four instances of condensate (16%), and three instances of treated geofluid (12%) (Figure 5). There are 25 data points for 16 projects due to multiple sources being used for several projects.

From this analysis, we can conclude several things. First of all, that groundwater is by far the preferred source of water, if available. For the projects that used surface water, this was usually because groundwater in the area was unfit for the needed purpose or unavailable. This was especially the case with operational water usage. If groundwater quality is not sufficient for cycling through a geothermal power plant, and treatment is too expensive, surface water is often the alternative. For example, this is the case for some of the Innamincka Deep wells in Australia, where the groundwater is too high in calcium for stimulation purposes; thus, surface water from

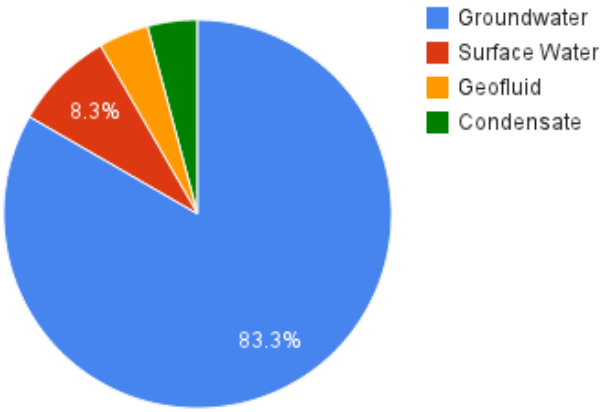

FIGURE 3 Water Sources for Drilling Activities

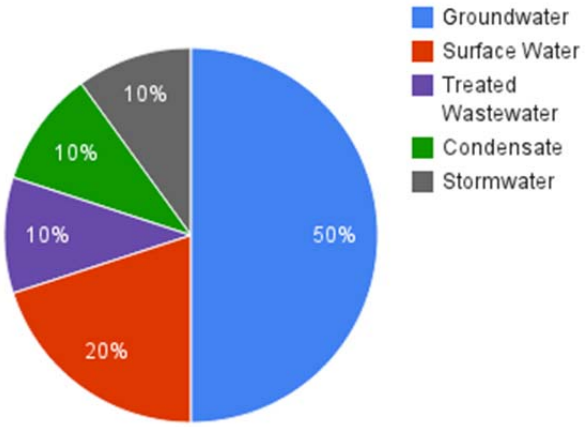

FIGURE 4 Water Sources for Stimulation

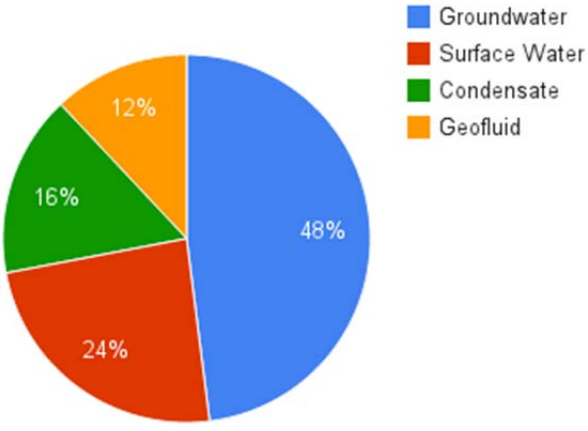

FIGURE 5 Water Sources for Aboveground Operations

Cooper Creek is used instead (Geodynamics 2011). This is also the case in much of the Salton Sea geothermal area, where groundwater is scarce, so surface water is used instead. Secondly, a variety of approaches appear to be employed for stimulating EGSs. While groundwater is the dominant source, several projects use other sources of water if available, like treated wastewater, condensate, and even stormwater. The specialized nature of these projects means that these alternative sources tend to be considered in addition to traditional sources like groundwater and surface water.

3.7 WATER QUALITY ISSUES

Argonne previously completed a thorough review and analysis of geothermal water quality and water chemistry characteristics (Clark et al. 2011). The analysis found that geofluid quality can vary substantially between geothermal fields, geothermal wells, and even within the same well over time. The previous work focused on aggregating and analyzing available data of approximately 3,100 moderate- and high-temperature data points, referred to as the Argonne Geothermal Geochemical Database (AGGD). Analyzing these data points yielded information on geofluid composition, analysis of scale and corrosion potential, human health risks, and comparison with U.S. drinking water standards. Trends for metrics such as TDS, pH, and major geofluid constituents were also developed.

The current analysis aimed to serve as an extension of this work on geofluid water quality, while at the same time expanding it by focusing particularly on the challenges that water quality presents for work with EGSs. By focusing on EGS data points, both domestic and international, within the Project Database, the intent was to gain insight into how water chemistry affects these projects.

The EGS projects that provided sufficient, specific water quality data included the Soultz-sous-Forêts in France, the Innamincka Deep project in Australia, the Geysers in California, the Newberry Volcano project in Oregon, and the Desert Peak project in Nevada. However, not all of the projects provided the same information, and information provided about stimulation generally centered around quantities of water and pressure needed, rather than the water quality itself. Therefore, our analysis was limited to projects that specifically mentioned relevant water quality metrics.

Only Soultz-sous-Forêts reported pH; thus, comparisons with hydrothermal systems are of limited value. However, the EGS project appears to be within the range of projects within the AGGD. Clark et al. (2011) found that pH values appear to be roughly distributed around a median of 7.3, with most projects falling between 4.5 and 10.0. Soultz-sous-Forêts reported a pH range of 4.9 to 5.3 in its EGS reservoir (Scheiber et al. 2012).

Water quality characteristics vary widely among EGS reservoirs. In terms of dissolved solids, Clark et al. (2011) reported that 80% of TDS samples in the AGGD had a value of less than 5,000 mg/L. Similarly, the EGS project at Desert Peak in Nevada reported a geofluid TDS value of 7,000 ppm, which is within the same order of magnitude (BLM 2003). Although Clark et al. (2011) found that the majority of TDS measurements were clustered between 500

and 5,000 mg/L, some reservoirs have TDS values outside this range. For example, the Soultz-sous-Forêts EGS reservoir reported TDS readings significantly below this range, at 95 mg/L (Scheiber et al. 2012), and the Geysers in California reports ranges from 130 to 340 mg/L (RMT, Inc. 2010).

Chemical constituents also tend to be very similar for conventional geothermal waters and EGS reservoirs. The major constituents reported by Clark et al. (2011) for geothermal samples from the AGGD included sodium chloride (NaCl), bicarbonate (HCO_3), sulfate (SO_4^{2-}), silica (SiO_2), calcium (Ca), and potassium (K). This closely mirrors chemical constituents found in EGS projects. For example, at the Geysers in California, the groundwater quality was found to be relatively hard because of the presence of Ca^{2+} and magnesium (Mg^{2+}) cations, though the water quality was ultimately found to be sufficient for reservoir stimulation (RMT, Inc. 2010). Similarly, at the Soultz-sous-Forêts, major constituents included Na^+, K^+, Ca^{2+}, chlorine (Cl^-), and SO_4^{2-} (Scheiber et al. 2012).

Water quality presents important and unique challenges to EGSs, particularly with stimulation. For example, in Australia's Cooper Basin, the Innamincka Deep EGS project reported that shallow groundwater wells in the area had TDS values between 1,000 and 10,000 mg/L (Geodynamics 2010). While these levels do not necessarily pose a problem, the presence of elevated levels of Ca^{2+} indicated that this water was not of sufficient quality for reservoir stimulation, and surface water sources were instead resorted to for this operation (Geodynamics 2008).

The presence of cations such as Ca^{2+} in an EGS reservoir can be problematic due to issues of scaling. Because the solubility of Ca^{2+} decreases with increasing temperature, it tends to precipitate out of solution as the groundwater is injected for stimulation, and the temperature of the stimulation fluid increases due to contact with the reservoir. The temperature increase, combined with the pressure drops that occur during stimulation, can result in significant scaling problems on the geothermal power equipment, as well as scaling along the well and fracture network that stimulation is meant to open and expand (Clark et al. 2011).

Scaling has been a significant issue for the Soultz-sous-Forêts EGS project because it has collected on power plant equipment, including the filters, pipes, and heat exchangers. The scale formed on site most often included barium/strontium sulfates, lead sulfides, and other mixed sulfides, and most commonly occurred on the cool part of the power plant due to temperature decreases from the heat exchanger (Scheiber et al. 2012). Other scales, referred to as cuttings, were actually raised from the reservoir itself. Some EGS projects, such as the Groβ Schönebeck site in Germany, have had luck with mixing injection fluid with small amounts of acetic acid in order to "set" the pH artificially and prevent and treat iron scaling issues (Zimmermann et al. 2009).

In addition to the sulfate and sulfide scaling that Soultz-sous-Forêts experienced, correlations have been observed between scale development and radionuclide concentrations. In a study of the plant's operations during 2010 and 2012, an increase in naturally occurring radioactive material (NORM) was observed in parallel with increases in circulation volume, with

the highest values found close to the reinjection point where the temperature is lower (Genter et al. 2012).

Recent work on the Calpine Geysers EGS project has shown a correlation between stimulation activities; that is, the injection of water underground and subsequent readings of noncondensable gases (NCGs) (Garcia et al. 2012). Stimulation of one well at the Geysers resulted in a decrease of NCG from 3.7 to 1.1 wt% over the course of approximately a year and a half (Garcia et al. 2012). This decrease in NCG concentrations may be due to dilution inside the reservoir with the addition of large volumes of water being injected during the stimulation of the well.

4 INTEGRATION OF RESULTS WITH LIFE CYCLE

Aggregating the collected data, water consumption was quantified at each stage of the geothermal power plant life cycle normalized for each of the developed technology scenarios per lifetime energy output, for comparison across power generation technologies and integration with the water resource assessment. Table 9 presents the aggregated data as they were applied to each of the developed power plant scenarios. The derivations of the specific values in this table are described in more detail in the following sections.

4.1 WATER CONSUMPTION ESTIMATES FOR THE CONSTRUCTION STAGES

Through normalization, it is apparent that the vast majority of water consumption occurs during operations (Table 9). This is consistent with the previous analysis by Clark et al. (2011). For hydrothermal systems, drilling and cementing wells are the next largest water consumer. For EGS, the water consumption associated with drilling and cementing is similar to stimulation and circulation testing depending upon the estimation method used.

The following two approaches were used to estimate water volumes for drilling and constructing wells: (1) estimates provided in the literature and (2) estimates based upon well designs as discussed in Clark et al. (2011). As seen in Table 10, estimates in the literature report consumption that is twice that of the well design estimates. The literature reported maximum projections of daily water volumes during the drilling period (e.g., BLM 2010c,e; 2011b). Because the literature values did not have supporting information justifying the estimates, the estimates according to well design were incorporated into the life cycle water analysis; although data were collected for observation and exploration wells, the life cycle water consumption estimates were based only upon total production and injection wells. This is because the water burden of any exploration wells that do not become production or injection wells would likely be shared among plants developed within a geothermal area.

For EGS, stimulation is also a significant water consumer. The literature review indicated that a typical stimulation job requires approximately 19,400 m^3 (5,125,000 gal), which is slightly less than the 20,000 m^3 (5,283,000 gal) used in the previous analysis (Clark et al. 2011). This estimate on a per-well basis is within the range of consumption estimates for hydraulic fracturing for natural gas extraction in low-flow plays such as shale (8,700–201,000 m^3 [2,300,000–5,500,000 gal]) (GWPC and ALL 2009). It is not appropriate to compare the performance over the lifetime as these are not comparable resources. Unconventional gas wells experience rapid decline in energy output, whereas EGS wells are expected to deliver a relatively consistent supply of energy to a power plant over a 30-year lifetime.

For the scenarios examined, stimulation was found to consume a similar volume of water as that used when drilling and cementing wells. This is due to the assumption that only injection wells would be stimulated and that the ratio of production to injection wells is 2 to 1. For projects where these conditions are not met, consumption volumes may not be as comparable.

TABLE 9 Water Consumption Estimates by Gallon and Gallon per Kilowatt-Hour Lifetime Energy Output for Each Significant Life Cycle Stage

Life Cycle Water Consumption in gal (gal/kWh)	20-MW Dry EGS Binary	50-MW Dry EGS Binary	10-MW Dry Hydrothermal Binary	50-MW Wet Hydrothermal Flash
Drilling, design	15,000,000 (0.003)	38,000,000 (0.003)	1,400,000 (0.001)	14,000,000 (0.001)
Drilling, literature	30,000,000 (0.006)	74,000,000 (0.006)	3,400,000 (0.001)	27,000,000 (0.002)
Stimulation	16,000,000 (0.003)	41,000,000 (0.003)	NA[a] NA	NA NA
Circulation, testing	15,000,000 (0.003)	36,000,000 (0.003)	NA NA	NA NA
Pipeline	39,000 (0.00001)	98,000 (0.00001)	18,000 (0.00001)	90,000 (0.00001)
Power plant	210,000 (0.00004)	540,000 (0.00004)	110,000 (0.00004)	180,000 (0.00001)
Operations, aboveground fresh water	210,000,000 (0.04)	530,000,000 (0.04)	110,000,000 (0.04)	530,000,000 (0.04)
Operations, aboveground geofluid	NA NA	NA NA	NA NA	35,000,000,000 (2.7)
Operations, belowground (assume 5% loss)	4,700,000,000 (0.9)	12,000,000,000 (0.9)	NA NA	NA NA

[a] For those stages that are not present in a specific scenario, NA (not applicable) is used.

Throughout the stimulation stage for EGS projects is a series of flow tests that require water. Accounting for pre-stimulation, post-stimulation, short-term circulation, and long-term circulation tests, the water consumed for circulation testing is similar to the volumes required for drilling and cementing and stimulating per lifetime energy output for the EGS scenarios. There is a great deal of uncertainty on the water volume required for long-term, commercial-scale circulation testing. Projects to date have been small-scale proof of concepts. As a result, circulation testing consumption estimates may change in the future as commercial-scale projects are developed.

Water consumption for the development of the pipeline and the power plant were determined to be negligible per lifetime energy output in the previous analysis (Clark et al. 2011). As a result, no additional analysis was undertaken for this work, and the

estimates from the previous report were maintained for the overall water consumption over the life cycle.

4.2 ABOVEGROUND OPERATIONAL WATER CONSUMPTION

Operational water consumption remains the stage of the geothermal life cycle where the highest degree of uncertainty remains. It is also the stage with the greatest impact on the full life cycle water consumption, at least for conventional geothermal systems. To improve understanding of operational water consumption, consumption was separated according to aboveground water loss and belowground water loss.

Previous Argonne estimates of operational water consumption were based upon very limited data and focused on aboveground consumption only. Operational water consumption was estimated to be 0.27 gal/kWh for dry-cooled binary plants, 0.01 gal/kWh for flash plants, and 0.27 to 0.72 gal/kWh for dry-cooled binary EGS plants, based upon production and injection data from five existing hydrothermal power plants in California (Clark et al. 2011, 2012). These estimates were based upon the assumption that during months when reported injection exceeded reported production, the difference was the result of external makeup water being added to the reservoir. In months where production exceeded injection, this was assumed to result from a loss of geofluid at the surface. For binary and flash systems, the water consumption estimates were based upon those calculated for makeup water requirements. For EGS, the low estimate for makeup requirement was based upon the above assumptions, and the high estimate was based upon the geofluid loss estimate. Recent discussions with state officials and industry representatives, however, have called into question the reliability of the data upon which these analyses were based, as discussed in Section 3.5. For this reason, this previous approach was not used here; instead, data collected from the literature and document review were used.

The data gathered from the more extensive literature review presented in Section 3.5 and Appendix D provide a stronger basis for estimating the operational water consumption from geothermal power plants. The existing LCA scenarios are based upon dry cooling systems. For these systems, the average water consumption from the literature review was used for operational water consumption. The operational water consumption for dry cooling systems includes all noncooling-related water consumption during daily operations such as dust control, maintenance, and domestic use. The average value of 0.04 gal/kWh for dry-cooled systems from Section 3.5 was used for these systems. This value was also used for the noncooling-related water consumption for the flash system.

The flash scenario assumes wet cooling utilizing condensed geofluid for cooling. The scenario assumes a 30-year plant lifetime with no geofluid replacement. This results in a loss of geofluid that is not replaced, and, therefore, is not included within the fresh water consumption total. The fact that geofluid is not replaced will ultimately reduce the lifetime of the reservoir. Determining when and if replacement fluid should be injected into the reservoir to extend its lifetime is a question that must be answered independently at each power plant based upon the economics and the local availability of water. At least three geothermal power plants (Geysers, Coso, and Dixie Valley) have operated injection programs to supplement declining reservoirs.

The operational water consumption values for each of the LCA scenarios are summarized in Table 10. The table also includes geopressured systems evaluated previously, but not discussed in detail or re-evaluated here (Clark et al. 2012). The operational water consumption is broken down into fresh water consumption and geofluid consumption. Geofluid consumption only occurs in flash and geopressured systems.

Geofluid consumption is extremely high in geopressured systems because these systems often have high reservoir pressures that make reinjection of geofluid impractical. In these systems, the spent geofluid is typically disposed of in an injection well in a separate formation with higher injectivity. However, it is possible that over time, as the pressure in the reservoir declines, reinjection into the geopressured reservoir may become feasible, thereby reducing the geofluid consumption and helping to stabilize production later in the life of the power plant.

4.3 BELOWGROUND OPERATIONAL WATER REQUIREMENTS

Belowground losses for EGS are highly variable from formation to formation and difficult to predict a priori. Given that large flow rates of geofluid are required to operate geothermal power systems, even small percentage losses of fluid to the surrounding reservoir can add up to significant quantities of fluid over the lifetime of a power plant.

Table 11 shows the makeup water requirements for the EGS life cycle scenarios as a function of reservoir loss percentages from 1 to 20%. On the basis of the limited test data available in the literature presented in Section 3.5, loss rates for viable projects will likely range from 1 to 10%. Loss rates above 10% will also likely occur; however, it is unclear if those projects will be viable or will be considered failed projects and abandoned. At a loss rate of 20%, the water requirement is quite significant, although within the range of loss rates for existing wet-cooled systems presented in Section 3.4. The exact upper limit cutoff for EGS project viability is uncertain and likely to be location and project dependent. Reservoir losses should be considered among the many risks to project success when assessing any new EGS project. Improved understanding of what geological factors influence reservoir losses will be important to improve loss predictions and reduce project risk.

Given the high uncertainty associated with belowground operational water requirements, the full range of feasible loss rates from 1 to 10% were considered for the EGS LCA scenarios. This gives a range of 0.18 to 1.8 gal/kWh for belowground operational water requirements. The midpoint of the range, 5%, was assumed for the baseline resource assessment scenarios, where a single value was required. It is important to note that while fresh water may be used for supplemental injection, the water does not necessarily have to be of high quality. The fluid that is used does, however, have to be chemically compatible with the formation. The most important factor when determining water quality requirements for injected fluid is likely to be concentrations of scale-forming compounds. Concentrations of calcium are of particular importance since calcite solubility declines with increasing temperatures and can precipitate within the reservoir as the fluid is heated, potentially reducing the injectivity of injection wells (Clark et al. 2011).

TABLE 10 Summary of Operational Water Consumption for LCA Scenarios

Scenario	Cooling Type	Operational Fresh Water Consumption (gal/kWh)	Operational Geofluid Consumption (gal/kWh)
20-MW EGS Binary	Dry	0.04	0
50-MW EGS Binary	Dry	0.04	0
10-MW Hydrothermal Binary	Dry	0.04	0
50-MW Hydrothermal Flash	Wet	0.04	2.7
Geopressured[a]	Dry	0.04	23.7

[a] Clark et al. (2012).

TABLE 11 Makeup Water Requirements for EGSs as a Function of Reservoir Loss

Average Fluid Loss Rate (%)	Makeup Water Requirement (gal/kWh)	Makeup Water Flow Rate (gal/min/MW)[a]
20	3.6	60
10	1.8	30
5	0.90	15
2	0.36	6
1	0.18	3

[a] The flow rate assumes the average flow rate for the EGS scenarios as specified in Clark et al. (2011) of 434,000 gal/day/MW at 370°F (188°C).

4.4 RESULTS AND DISCUSSION OF LIFE CYCLE

Combining the water consumption for each stage of the life cycle results in estimates that differ from the previous analysis. Table 12 presents the revised analysis and compares the results with the previous analysis. Water consumption estimates for the air-cooled EGS binary scenarios increased due to the inclusion of belowground operational losses in the analysis. Water consumption for air-cooled hydrothermal binary plants decreased considerably based upon the new approach to determine aboveground operational water consumption. Wet-cooled hydrothermal flash estimates increased slightly, assuming that all cooling water needs are met through the use of geofluid and that fresh water consumption is for noncooling water needs. Geopressured systems were not included in the revised analysis. Although geopressured systems are likely to have aboveground operational consumption that is noncooling related, data for geopressured systems are insufficient to reassess at this time.

Few studies have evaluated water consumption for geothermal technologies. Frick et al. (2010) conducted an LCA on enhanced low-temperature binary systems by using wet cooling

TABLE 12 Total Life Cycle Estimates for Various Geothermal Technologies in Gallons per Kilowatt-Hour[a]

Power Plant	Plant Construction	Plant Operations (aboveground)	Plant Operations (belowground)	Total Life Cycle	Previous Total Life Cycle Estimate[c]
Dry EGS binary	0.009	0.04	0.18–1.81[b]	0.22–1.85	0.30–0.73
Dry hydrothermal binary	0.001	0.04	–	0.04	0.15–0.271
Wet hydrothermal flash	0.001	0.04 (2.7)	–	0.04 (2.7)	0.01 (2.7)
Geopressured[d]	0.0004–0.0005	– (23.7)	–	Not reassessed	0.0004–0.0005 (23.7)

[a] Numbers in parentheses represent lost geofluid.
[b] Accounts for 1 to 10% belowground operational water loss.
[c] Clark et al. (2011, 2012).
[d] Based upon allocation assumption of 3.6 MW generated via geothermal and 17.4 MW generated via natural gas.

and found an aggregate consumption of 0.36 gal/kWh over the lifetime energy output. However, Frick et al. (2010) identifies the construction stage, particularly "reservoir enhancement," as the stage primarily responsible for the water consumption requirements. If reservoir enhancement includes makeup water to address declining geofluid water volumes over time, some of the volume may be accounted for in the makeup water requirements identified in the belowground operations stage of the EGS power plant life cycles presented here. The estimate in Frick et al. (2010) is within the expected range of water consumption for EGS from the current analysis. Hydrothermal binary, hydrothermal flash, and geopressured geothermal when compared with other power generation technologies are among the lowest fresh water consumers per lifetime energy output as shown in Figure 6. The uncertainty of belowground operational water consumption for EGS makes a comparison more difficult. But by using a target of 5% belowground operational loss, EGS binary is one of the higher water consumers and is comparable to concentrated solar power and coal with carbon capture. However, as the additional water for EGS binary is for maintaining the reservoir and not for cooling purposes, the water need not be of high quality. It should be noted that if the dry-cooled hydrothermal or EGS binary systems were wet or hybrid cooled, the water consumption would increase significantly due to cooling water requirements as shown in Figure 2 in Section 3.4. Additional LCA scenarios, including multiple cooling systems, will be considered in future studies.

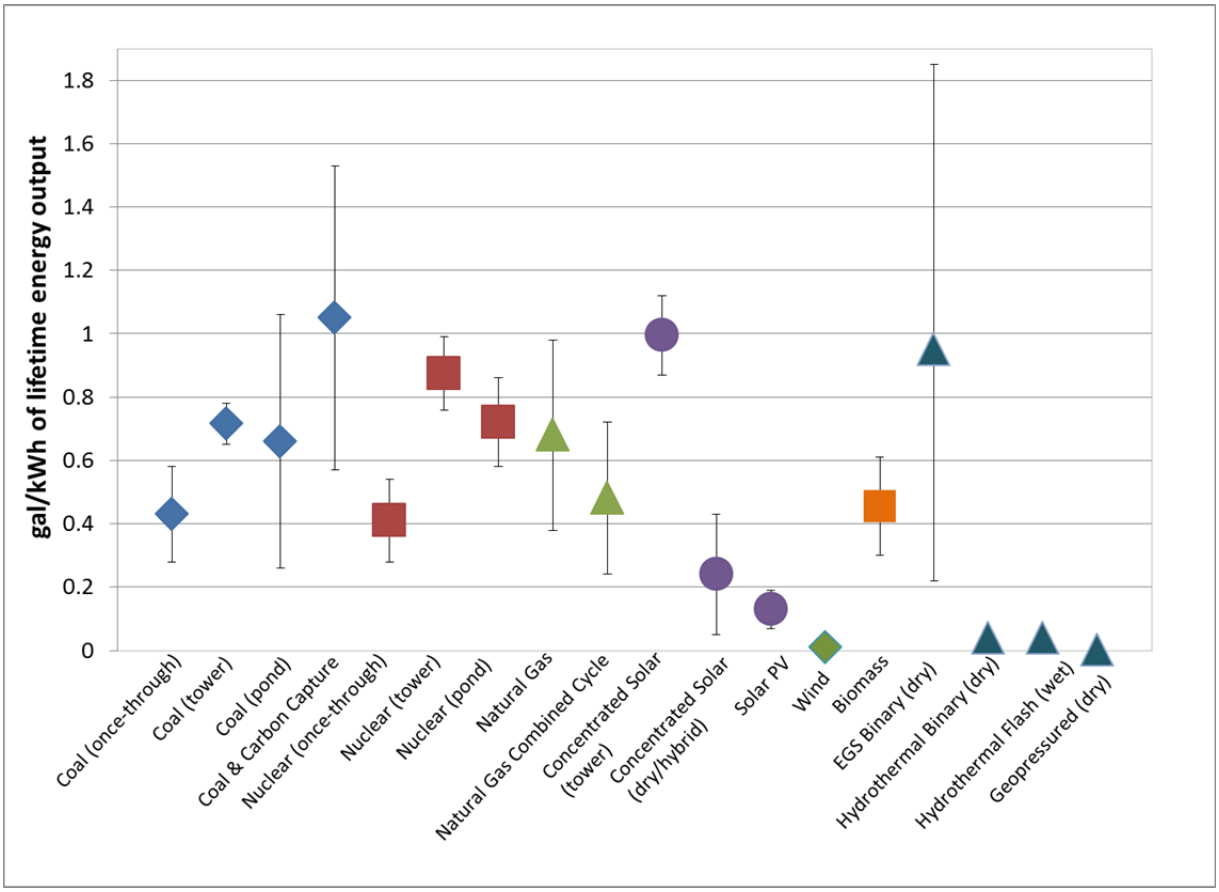

FIGURE 6 Water Consumption per Lifetime Energy Output of Various Electricity Generation Technologies

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5 WATER RESOURCE ASSESSMENT

The regional water resource assessment explores the spatial distribution of geothermal resources and their estimated water consumption if developed. A range of geothermal growth scenarios were mapped and explored for their water consumption implications. A number of water availability metrics are also presented which are used to identify areas where limited water availability is most likely to affect the development of geothermal resources.

5.1 WATER CONSUMPTION FACTORS

Water consumption estimates for the regional water resource assessment were based upon water consumption factors taken from the LCA results presented in Section 4.2. Identified or unidentified hydrothermal resources with a temperature above 225°C (437°F) were treated as potential areas for the development of *hydrothermal flash systems* with fresh water consumption of 0.04 gal/kWh. Identified or unidentified hydrothermal resources with a temperature below 225°C (437°F) were treated as potential areas for the development of *hydrothermal binary systems* with fresh water consumption also of 0.04 gal/kWh. All areas with potential for the development of EGS resources, both near-field and greenfield EGS, were assumed to be from binary systems with a 5% belowground operational water loss leading to total water consumption of 0.95 gal/kWh. For this analysis, it was assumed that all belowground losses would be made up with fresh water. This is a conservative assumption as it may be possible to meet some or all of this water demand from nonpotable sources. To test this sensitivity, one of the growth scenarios was run assuming no fresh water use to make up for belowground water losses. In this scenario, fresh water consumption was set to 0.05 gal/kWh for EGS resources. All water consumption factors were applied to the resources in the supply curve assuming a 90% capacity factor based upon the estimated generation capacity potential for each resource.

5.2 SCENARIO DEFINITIONS

A total of 15 GIS maps were generated for different scenarios representing varying levels of future growth in geothermal electricity generation. The growth 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 growth scenarios are described in Table 13.

The first set of scenarios looks at the total geothermal potential and water consumption, assuming complete development of the entire resource base for three different resource types: identified hydrothermal, unidentified hydrothermal, and near-field EGS. Greenfield EGS resources were not mapped because the resource potential vastly exceeds the other three categories, is more uniformly distributed, and the resource is unlikely to ever become fully exploited. However, the total resource potential for greenfield EGS resources was calculated at depths of up to 6 km (4 mi) and up to 10 km (6 mi), along with the expected water consumption. Both of these quantities were also calculated for resources within NEMS Regions 11, 12, and 13, which include 11 western states that match most closely with the geographical area covered by

TABLE 13 Regional Water Resource Assessment Scenario Descriptions

Scenario Title	Scenario Description
All identified geothermal resources	All identified resources
All unidentified geothermal resources	All unidentified resources
All near-field EGS resources	All near-field EGS resources
All resources < $0.05/kWh, target cost curve	All resources ≤ $0.05/kWh, target cost curve
All resources < $0.05/kWh, base cost curve	All resources ≤ $0.05/kWh, base cost curve
All resources < $0.10/kWh, target cost curve	All resources ≤ $0.10/kWh, target cost curve
All resources < $0.10/kWh, base cost curve	All resources ≤ $0.10/kWh, base cost curve
All resources < $0.15/kWh, target cost curve	All resources ≤ $0.15/kWh, target cost curve
All resources < $0.15/kWh, base cost curve	All resources ≤ $0.15/kWh, base cost curve
All resources < $0.20/kWh, target cost curve	All resources ≤ $0.20/kWh, target cost curve
All resources < $0.20/kWh, base cost curve	All resources ≤ $0.20/kWh, base cost curve
NEMS-GPRA 2030 growth scenario, base cost curve	7.9 GW of new generation in 2030 based on NEMS results with base cost curve
NEMS-GPRA 2030 growth scenario, target cost curve	11.5 GW of new generation in 2030 based on NEMS results with target cost curve
NEMS-GPRA 2030 growth scenario, target cost curve, no EGS reservoir loss	11.5 GW of new generation in 2030 based on NEMS results with target cost curve, assumes EGS makeup not from fresh water
EIA Annual Energy Outlook 2012 2035 growth scenario, target cost curve	3.9 GW of new generation in 2035 based upon the EIA's 2012 Annual Energy Outlook

the other three geothermal resource categories and for the entire United States.

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 geothermal supply curves.

The final set of four scenarios looks at results from the EIA's NEMS integrated energy model, which focuses on likely energy development over the next few decades (EIA 2011). Two scenarios are based upon a version that was 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 fourth quarter meeting of the Geothermal Strategic Planning and Analysis Working Group (Wood and Dublin 2010), showed growth in geothermal electricity production of 7.9 GWe by 2030 for the base supply curve and 11.5 GWe for the target supply curve. The previous analysis (Clark et al. 2012) used values of 10.4 and 14.0 GWe, which failed to subtract existing geothermal generation from the total. A third scenario is based upon these same modeling results for the target supply curve but use a lower water consumption factor of 0.05 gal/kWh for EGSs. The basis of this lower consumption factor is the assumption that belowground operational losses for EGSs would be made up by utilizing non-fresh-water sources, thereby limiting the impact on fresh water resources. The fourth scenario is based upon

NEMS model results presented in the EIA's 2012 *Annual Energy Outlook* that show growth in geothermal electricity production of 3.9 GW by 2035 (EIA 2012). To replicate these growth scenarios, geothermal resources were selected beginning with the lowest LCOE and proceeding to the highest LCOE until the total electricity generation equaled the total generation potential for the scenario. This set of scenarios includes realistic estimates of geothermal growth rates and allows for the identification and analysis of possible near- and intermediate-term water-related challenges.

5.3 WATER DEMAND RESULTS

Table 14 gives the water demand scenario results. It summarizes the total new generation, total water consumption in acre-feet per year (ac-ft/yr), and the average water intensity for new geothermal generation in gal/kWh for each scenario. Maps illustrating the geographical distribution of water demand for new geothermal development for each scenario can be found in Appendix E. The totals in the table include resources in Alaska and Hawaii, which are not included on the maps.

Most of the scenarios included here were previously mapped and analyzed at a state-by-state level in previous work with slightly different water consumption factors (Clark et al. 2012). The biggest difference in the water consumption values is that the water consumption factor used for binary was reduced from 0.27 to 0.04 gal/kWh, and the water consumption factor for EGSs was increased from 0.51 to 0.95 gal/kWh. However, most of the general trends from the previous analysis still hold. As you move up the cost curve to higher cost resources, more EGSs tend to be included in the scenarios, which significantly increases water consumption. Also moving from the base cost curve to the target cost curve, which assumes reduced costs for EGS based upon learning and technological improvements, increases resource potential at the same cost but comes at the cost of increased water consumption. This is most clearly illustrated by comparing the target and base scenarios at $0.20/kWh, where the generation increases by a factor of 10 while the water consumption increases by a factor of 50 when moving from the base to target cost curves. Similarly for the NEMS-GPRA scenarios, moving from the base to target cost curves also results in a significant growth in generation and water consumption due to a higher fraction of EGS resources being developed under the target cost assumptions.

In the previous analysis, a separate map of the greenfield EGS resources was not included because there was not sufficient geospatial information provided in the geothermal supply curves for these resources. Under this effort, the greenfield EGS and unidentified hydrothermal data were interpolated with temperature at depth data to increase the spatial resolution as described in Section 2.6. With this higher resolution geospatial dataset, multiple analyses of the greenfield EGS potential were performed, considering both geographical extent and depth of resource as discussed in Section 5.2. The resource potential in each scenario, however, was too great to be meaningful in comparison with the other resource categories. The development of the extremely large, deep EGS resource will almost certainly be limited by many factors, water being one of them, but cost likely being the most important. An area of continued research will be to further

TABLE 14 Summary of Regional Water Resource Assessment Water Demand Results

Scenario	New Geothermal Generation (MW)	Water Consumption (ac-ft/yr)	Average Water Intensity (gal/kWh)
All identified geothermal resources	6,400	6,200	0.04
All unidentified geothermal resources	30,000	29,000	0.04
All near-field EGS resources	7,000	160,000	0.95
Greenfield EGS resources (NEMS 11–13 only)[a]	8,200,000	190,000,000	0.95
All greenfield EGS resources[a]	16,000,000	360,000,000	0.95
Greenfield EGS resources at ≤ 6 km (NEMS 11–13 only)[a]	1,700,000	39,000,000	0.95
All greenfield EGS resources at ≤ 6 km[a]	2,000,000	48,000,000	0.95
All resources < $0.05/kWh, target cost curve	3,400	12,000	0.15
All resources < $0.05/kWh, base cost curve	3,000	3,000	0.04
All resources < $0.10/kWh, target cost curve	30,000	130,000	0.18
All resources < $0.10/kWh, case cost curve	26,000	34,000	0.05
All resources < $0.15/kWh, target cost curve	58,000	770,000	0.55
All resources < $0.15/kWh, base cost curve	29,000	97,000	0.14
All resources < $0.20/kWh, target cost curve	300,000	6,300,000	0.88
All resources < $0.20/kWh, base cost curve	31,000	130,000	0.17
NEMS-GPRA 2030 growth scenario, base cost curve	8,000	8,000	0.04
NEMS-GPRA 2030 growth scenario, target cost curve	12,000	87,000	0.31
NEMS-GPRA 2030 growth scenario, target cost curve, no EGS reservoir loss	12,000	13,000	0.05
EIA Annual Energy Outlook 2012 2035 growth scenario, target cost curve	3,900	24,000	0.26

[a] These scenarios were not mapped; the total results are presented for comparative purposes.

explore where and when limited water availability and high water costs become a significant barrier to the development of these resources.

The larger difference compared with the previous analysis is the spatial resolution of the water consumption estimates. An example map is shown in Figure 7 (all maps are included in Appendix E). This map shows all resources at an LCOE of $0.10 or less based upon the target cost curve. This map best represents the geothermal resources that are most likely to be economically exploitable in the near and medium term. The areas that show the greatest water demand are in Nevada and southeastern and northern California. This is also consistent with the previous results that showed that the greatest resource potential and water demand were in the states of California and Nevada.

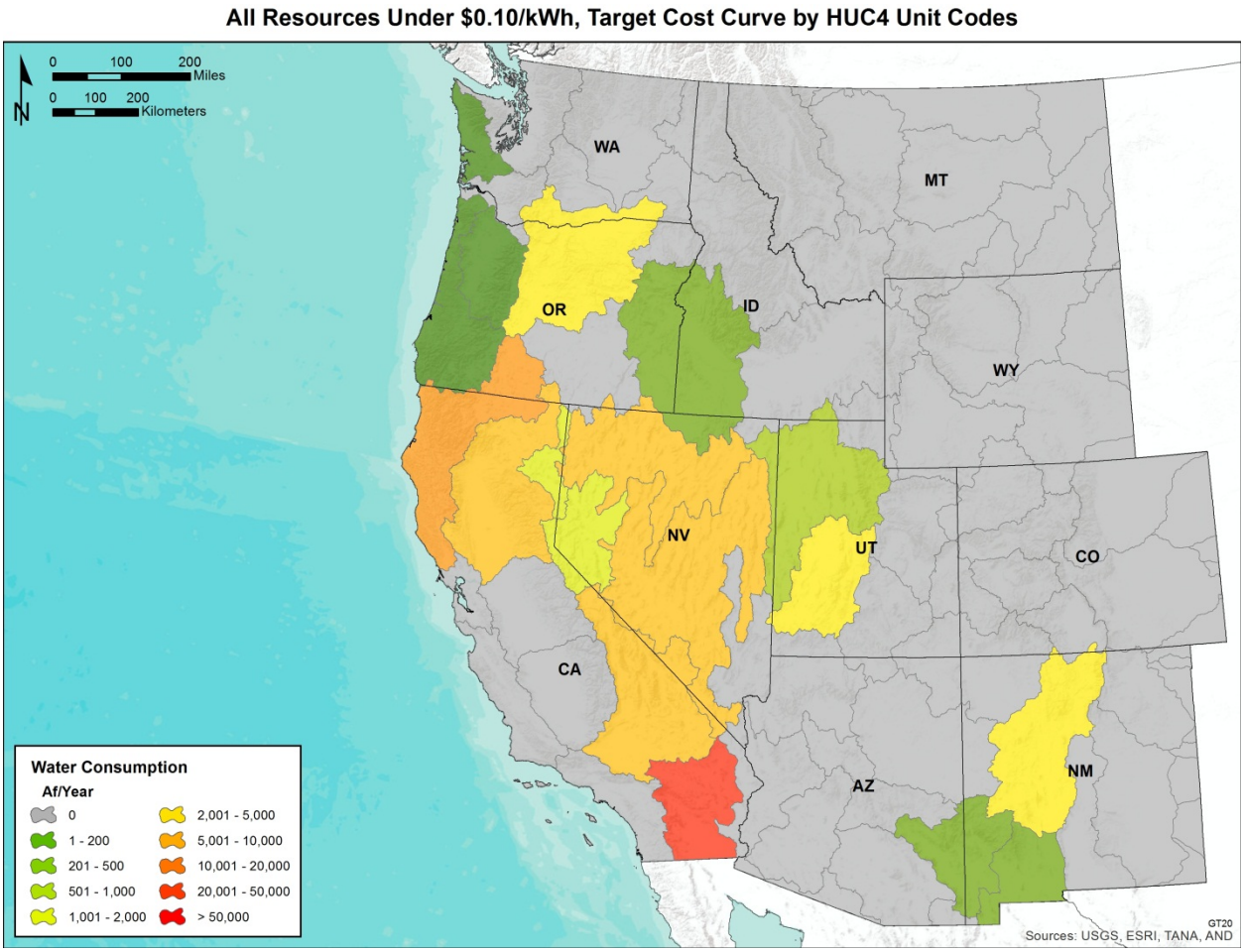

FIGURE 7 Water Consumption Scenario: All Resources under $0.10/kWh, Target Cost Curve

Figure 8 includes the maps for all four scenarios based on NEMS modeling results. The geographical distribution of the water demand is fairly similar in all four scenarios. In the NEMS-GPRA 2030 base cost curve scenario, the water demand remains low in nearly all basins due to the fact that EGS resources remain uneconomical in this scenario. Only one basin in southeastern California (HUC 1810) exceeds 1 million m^3/yr (1,000 ac-ft/yr), with water consumption of just more than 6 million m^3/yr (5,000 ac-ft/yr). When the target cost curve was used instead, the water consumption for this basin jumped up to more than 60 million m^3/yr (50,000 ac-ft/yr), while also increasing in all other basins. However, when nonpotable water was used for makeup of belowground operational water losses for EGSs, the water consumption dropped below 6 million m^3/yr (5,000 ac-ft/yr) in all basins. The EIA *Annual Energy Outlook* 2035 target scenario resulted in only half the generation capacity of the NEMS-GPRA 2030 base scenario, and a third of the generation of the NEMS-GPRA 2030 target scenario, but still resulted in nontrivial water consumption for two basins in California. A basin in northern California (HUC 1801) shows water consumption of 7 million m^3/yr (6,000 ac-ft/yr), due to the development of near-field EGS resources at the Geysers geothermal field. Southeastern California (HUC 1810) shows water consumption of 17 million m^3/yr (14,000 ac-ft/yr), due to

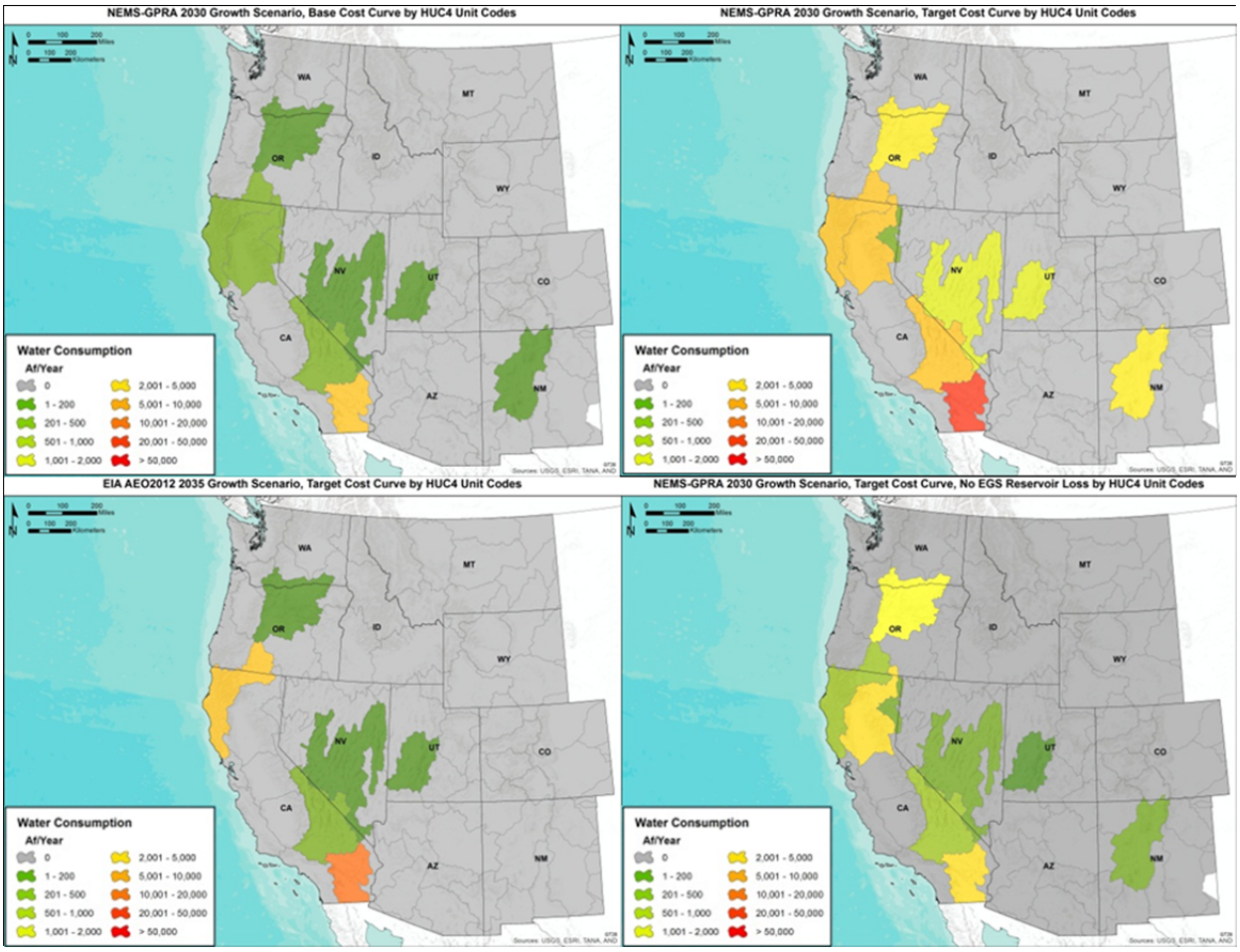

FIGURE 8 Water Consumption Scenarios: NEMS-GPRA 2030 Base Cost Curve (top left), NEMS-GPRA 2030 Target Cost Curve (top right), EIA Annual Energy Outlook 2035 Target Cost Curve (bottom left), and NEMS-GPRA 2030 Target Cost Curve No EGS Belowground Loss (bottom right)

the development of near-field EGS resources near the Salton Sea. The availability of water within these basins will be explored in Section 5.4 in an attempt to better understand the significance of these water volumes.

5.4 WATER AVAILABILITY RESULTS

Three sets of water availability metrics were explored, as described in Section 2.7. High-resolution maps of the water availability metrics are available in Appendix F. It is important to note that this analysis of water availability is pertinent to all new energy development in these areas, not just for geothermal. Areas identified as having low water availability or high water stress will be challenging for any new water consumers, and those energy technologies with the smallest water footprint are likely to have a competitive advantage.

Average and third percentile annual streamflow volumes for each HUC 4 basin are shown in Figure 9. Under average flow conditions, all basins that have significant geothermal potential have streamflow of more than 1 billion m^3/yr (1 million ac-ft/yr). However, under severe drought conditions represented by the third percentile flow conditions, streamflow in many important basins drops significantly. In southeastern California (HUC 1810), which has the highest estimated water demand for geothermal in many scenarios, the streamflow drops below 200 million m^3/yr (200,000 ac-ft/yr). While this is greater than the geothermal water demand in most scenarios, it still indicates significant water stress and potential challenges in obtaining water.

A second water availability metric was developed by combining water demand data with streamflow data and is illustrated in Figure 10. This metric measures stress on a watershed with higher values, indicating higher water stress. When this metric exceeds 1.0, it indicates either that all surface water would be consumed or that stored surface or groundwater must be consumed to supplement surface flows. Water demand estimates for 2030 were used for this metric to evaluate likely future water stress within the same time frame as many of the geothermal growth scenarios. Under normal flow conditions, the water stress is low to moderate in most basins except for a few in Arizona, southern California, and West Texas, with southern California having the greatest overlap with geothermal resources. Under severe drought conditions, the water stress significantly increases across most of the South and Mountain West. This indicates that water availability for most geothermal resources may become challenging under drought conditions.

A final set of water availability metrics was developed by Sandia National Laboratories, as described in Section 2.7. While the previous metrics only considered the physical availability of water, these metrics attempt to consider the political and economic availability of water in addition to physical availability. Figure 11 presents a summary of the estimated fresh water availability and total water availability. The fresh water availability metric includes unappropriated water: that is, water that might be available for purchase from low-value agriculture and renewable groundwater. The total water availability metric includes all of the fresh water sources plus estimates of brackish groundwater and municipal wastewater. These data indicate that water availability is fairly limited in most of the areas, with significant near- and medium-term geothermal potential. This highlights the importance of utilizing dry cooling systems when possible and minimizing fresh water consumption throughout the life cycle of geothermal power development.

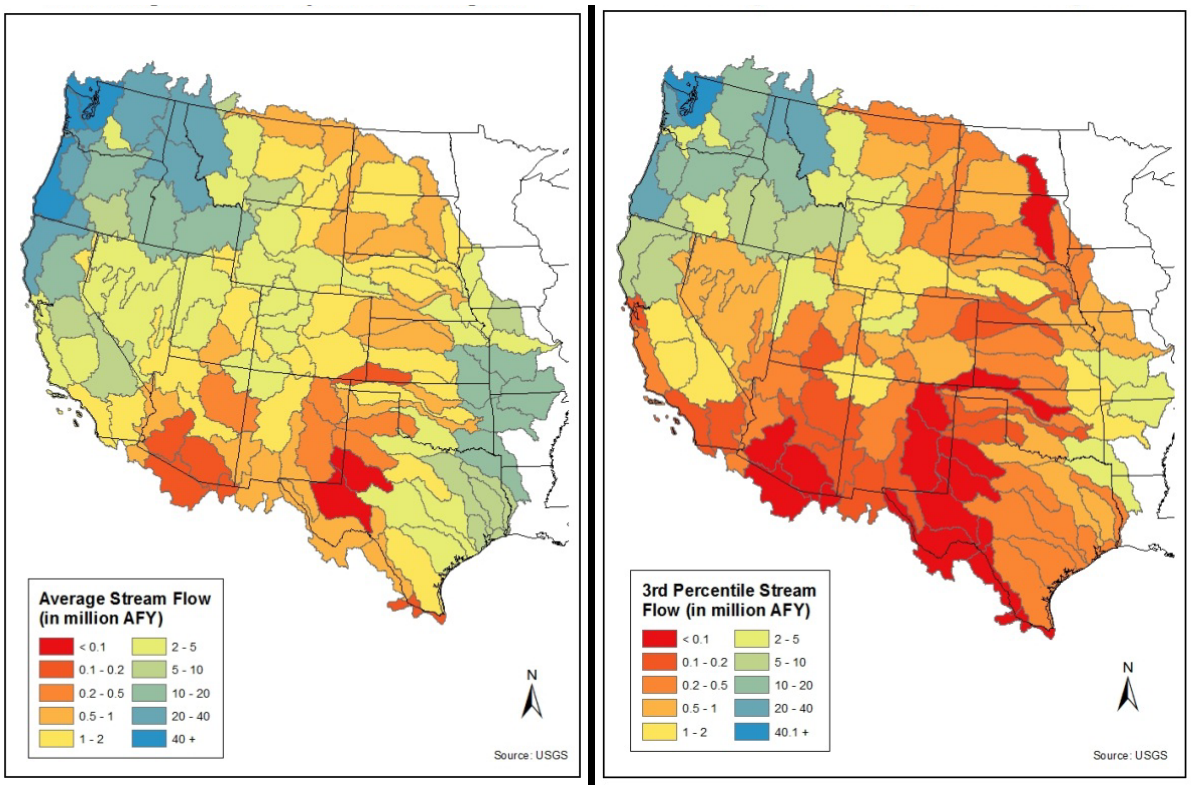

FIGURE 9 USGS Annual Streamflow Data 1950–2010: Average Streamflow (left) and Third Percentile Streamflow (right) (Source: USGS 2012)

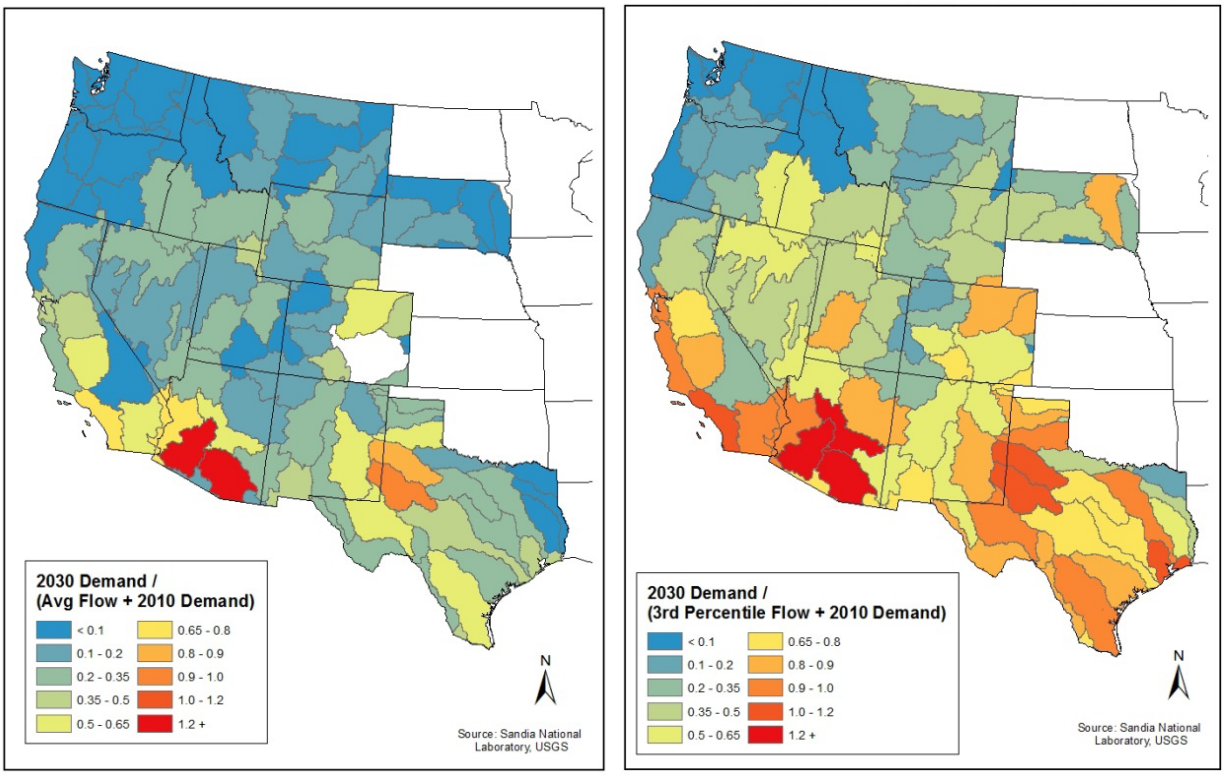

FIGURE 10 Water Availability Metric Defined as 2030 Water Demand Divided by the Streamflow Plus 2010 Water Demand: Streamflow Based on Average Streamflow (left) and Third Percentile Streamflow (right) (Sources: USGS 2012; Tidwell 2012)

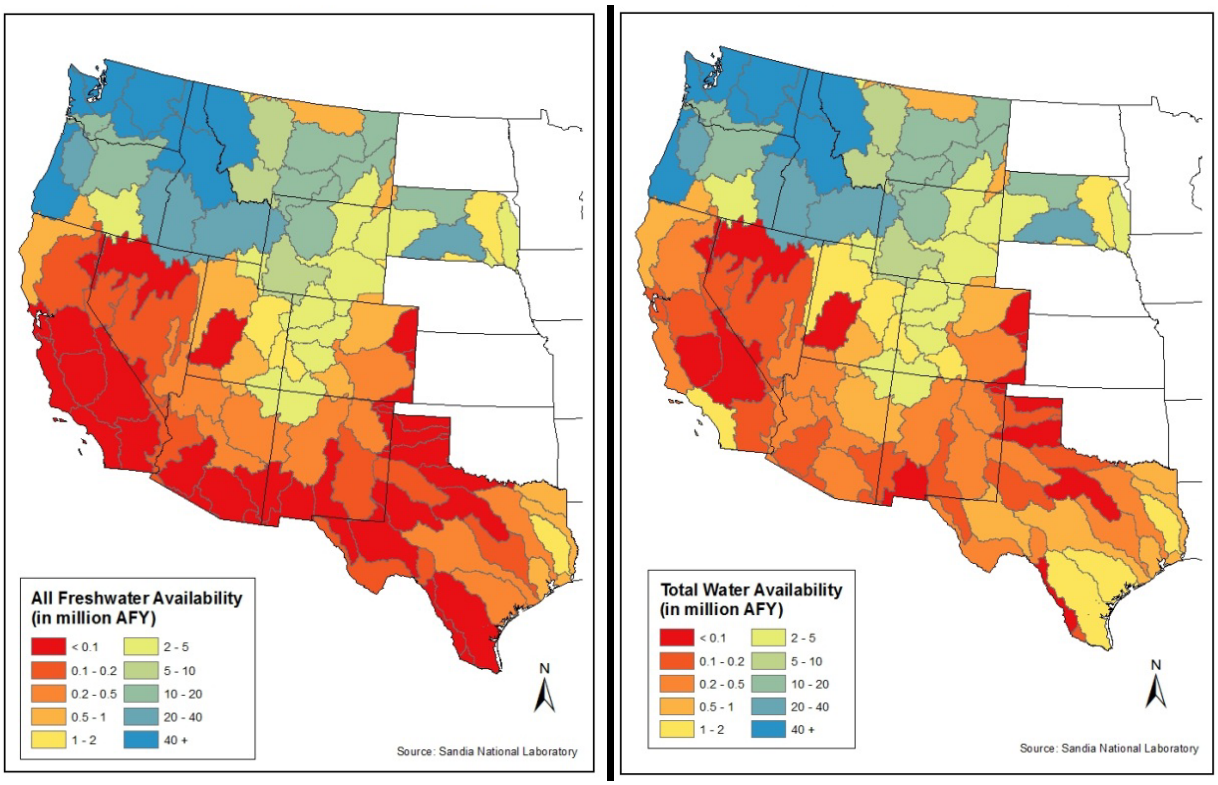

FIGURE 11 Water Availability Metrics Developed by Sandia National Laboratories: Fresh Water Availability (left) and Total Water Availability (right) (Source: Tidwell 2012)

6 SUMMARY AND CONCLUSIONS

A significant update to previous analyses of life cycle water consumption of geothermal power production and the regional impact on water resources was performed. The basis of the expanded analysis was an extensive literature review that went beyond peer-reviewed journal articles to include environmental documents required under NEPA and data collected by state agencies, including water permit applications and geofluid production and injection data. The improved LCA resulted in a slight increase in fresh water consumption for hydrothermal flash systems from 0.01 to 0.04 gal/kWh, and a decrease in water consumption for dry-cooled hydrothermal binary systems from 0.27 to 0.04 gal/kWh. These changes are primarily due to the utilization of unreliable production and injection data to estimate operational water consumption in the previous analysis. The current analysis is based upon more reliable estimates from the literature. Operations, however, remained the largest water consumer for these systems. These values hold only for dry-cooled binary systems and flash systems in which geofluid lost to cooling is not made up through supplemental injection programs. If, instead, wet or hybrid cooling systems are paired with binary plants, or if supplemental injection programs are instituted at flash plants to extend the life of the reservoir, the water consumption jumps substantially to an average of 2.4 gal/kWh for flash plants, 3.4 gal/kWh for wet-cooled binary plants, and 1.0 gal/kWh for hybrid-cooled binary plants. More extensive quantitative analysis of the tradeoffs inherent in the use of different cooling systems at geothermal power plants will be a focus of future work.

Total life cycle water requirements for EGS binary systems are much higher than those for the hydrothermal systems evaluated. Updated LCA results estimate water consumption varying between 0.22 and 1.85 gal/kWh for air-cooled systems, depending upon the extent of belowground operational water consumption. Relative to the previous LCA results of 0.27 to 0.72 gal/kWh, the aboveground operational water consumption was reduced by approximately an order of magnitude due to improved data. However, this reduction in aboveground operational water consumption was more than compensated for by the addition of belowground operational water losses that were not considered in the previous analysis. Belowground operational water loss is by far the greatest contributor to the life cycle, but it is also highly variable and dependent upon the physical and operational conditions of the reservoir, leading to wide uncertainty bounds. Of note, however, is the fact that makeup water for belowground losses will probably not have to be fresh water; thus the impact on water resources can be greatly reduced through the use of degraded water supplies such as brackish groundwater, municipal wastewater, or produced water. Despite garnering a lot of attention for requiring relatively large volumes of water over short periods of time, EGS reservoir stimulation activities were found to have a relatively small impact upon the total life cycle water consumption for EGS.

Although these results show a marked improvement in precision over previous analyses, a high degree of uncertainty remains both over aboveground water consumption for wet- and hybrid-cooled systems and for belowground water losses from EGSs. The uncertainty over aboveground water consumption could be significantly reduced through greater cooperation and voluntary disclosure by industry to make water consumption data available for existing,

operating geothermal power plants. The uncertainty over belowground losses for EGSs largely results from the limited number of EGS projects to date, but will improve over time as more test projects come online. With this in mind, it will be important to ensure that these projects collect the proper data and make that data available for researchers to better understand the process of system leak-off from EGS reservoirs.

The previous analysis of water demand for future growth in deployment of utility-scale geothermal power generation was also improved by increasing the spatial resolution and utilizing the updated LCA results. A total of 15 scenarios were evaluated, and the results were relatively consistent with the previous analysis. In general, the scenarios that assumed lower costs for EGSs, as a result of learning and technological improvements, resulted in greater geothermal potential but also significantly greater water demand due to the higher water consumption for EGSs. This effect, however, was shown to be largely mitigated if nonpotable water sources were used for belowground operational water demands. The geographical areas that showed the highest water demand for most scenarios were southern and northern California as well as most of Nevada.

In addition, an analysis of water availability was added to the regional water resource assessment. Maps were generated showing multiple water availability metrics covering the geographical areas identified as having the greatest geothermal potential. The data indicate that water availability is fairly limited, especially under drought conditions, in most of the areas with significant near- and medium-term geothermal potential. Southern California was found to have the greatest potential for water-related challenges with its combination of high geothermal potential and limited water availability. However, these areas with high water stress are likely to be challenging for all new energy development. The potential to minimize fresh water consumption throughout the life cycle of geothermal systems through the use of dry-cooling systems or degraded water sources may actually provide a competitive advantage compared with conventional power generation in these areas.

7 GLOSSARY[2]

Appropriated surface water: Surface water that is currently owned or being used by another party that may be available for sale or transfer.

Bridge plug: A tool used in downhole applications to isolate a lower zone, while an upper zone is being tested. It is applied into the wellbore or underground and has both permanent and temporary applications.

Chelating agents: Agents such as ethylenediaminetetraacetic acid (EDTA) and hydroxyethyl ethylenediamine triacetic acid (HEDTA) used to bind to metal ions to treat scale or prevent precipitation of compounds that otherwise could limit flow in the well or reduce the permeability of the reservoir.

Chemical well stimulation: The use of aqueous solutions to allow acids, bases, and chelating agents to be introduced into geothermal reservoirs.

Condensate: Water that has passed through the cooling system of a flash geothermal power plant.

Greenfield EGS resources: Hot rock formations not associated with existing hydrothermal resources, often found at depths greater than 4 km (2 mi). These resources require stimulation to create fractures for fluid circulation for power generation.

Enhanced geothermal system (EGS): Geothermal systems that require artificial enhancement of the reservoir to improve permeability and flow.

Exploration well: Any well drilled for the purpose of securing geological or geophysical information to be used in the exploration of oil, gas, geothermal, or other mineral resources.

Fracture acidizing: The acidic stimulation fluid is injected into the formation at sufficient pressure to cause a wellbore pressure buildup, which results in an increase in fracture length and width.

Fresh Water: Water from a surface or groundwater source that is of high quality and can be readily utilized for municipal, industrial, or agricultural uses.

Geofluid: Any fluid, liquid, or gas that occurs naturally in earthen formations, beds, or strata. In this report, it refers to the fluid from the geothermal reservoir, which is typically much warmer

[2] This glossary provides definitions of technical terms used throughout this paper. The first time each term is used it is *italicized*.

and has higher salinity and higher total dissolved solids concentrations than groundwater sources.

Groundwater: Water that is derived from aquifers and other sources belowground.

Hydraulic fracture stimulation: The injection of fluid at pressures above S_{hmin}, also known as the fracture initiation pressure, to create new fractures in the reservoir.

Hydraulic fracturing (fracking or fracing): A stimulation technique performed on low-permeability reservoirs to increase flow from the formation and improve productivity. Fluids and proppant are injected at high pressure and flow rate into a reservoir to create fractures that are often perpendicular to the wellbore according to the natural stresses of the formation and to maintain those openings during production.

Hydraulic shear stimulation: The injection of fluid at low pressures such that the least horizontal stress is not exceeded. This approach opens the existing fractures in the reservoir and does not create new fractures.

Hydraulic well stimulation: The introduction of water or a combination of water and gel-proppant fluids to a geothermal reservoir.

Hydrothermal binary system: A geothermal power plant that produces electricity from lower-temperature geothermal resources. This is a closed-loop system where the geothermal fluid is pumped from a well and flows through a heat exchanger to warm a secondary fluid, or "working fluid," which is directed to a turbine for power generation.

Hydrothermal flash system: A geothermal power plant that produces electricity from higher-temperature geothermal resources. The geofluid is rapidly vaporized or "flashed," and then the steam generated is directed to a turbine for power generation.

Identified hydrothermal geothermal resource: Resources that are known to exist and that are capable of supporting hydrothermal geothermal power systems.

Injection well: A well used for emplacing fluids into the subsurface.

Levelized cost of electricity (LCOE): A metric used to gauge the cost of a specific energy-producing system for comparison with other systems. It accounts for the life cycle cost to build and operate a power plant on a price-per-kilowatt-hour basis.

Life cycle analysis (LCA): A technique to assess environmental impacts associated with all the stages of a product's life from cradle-to-grave. An LCA is useful in providing an inventory of relevant inputs and environmental releases, evaluating the associated environmental impacts, and providing results for informed decisions.

Lithostratigraphy: A branch of stratigraphy dealing with the study of units of rock. Each unit is composed of a body of rock which is dominated by a certain lithology or similar color, mineralogic composition, and grain size.

Matrix acidizing: The acidic stimulation fluid is injected at a low enough pressure to prevent fracturing.

Municipal wastewater: Water that is discharged from a municipal wastewater treatment facility.

Near-field geothermal resources: Geothermal resources associated with identified hydrothermal resources that may require additional stimulation to be exploited.

Observation well: A well drilled for the purpose of observations such as water level or pressure recordings.

Packers: Mechanical devices used to isolate and target specific intervals of a well for treatment.

Potable groundwater: Fresh groundwater that is of sufficient quality for drinking.

Production well: A well used to retrieve fluid from an underground reservoir.

Proppant: Particles mixed with fracturing fluid to maintain fracture openings after hydraulic fracturing. These include sand grains or engineered materials.

Shallow brackish groundwater: Groundwater at a depth of between 15 and 762 m (50 and 2,500 ft) with salinity between 3,000 and 10,000 ppm total dissolved solids.

Stormwater: Atmospheric water that falls to the earth as precipitation and is then collected on the earth's surface.

Streamflow: The volume of water that moves over a designated point over a fixed period of time.

Surface water: Water that is available aboveground in a stream, lake, or river, and that can be obtained without drilling a well.

Thermal well stimulation: The introduction of chilled water, and thus cold stress, to a geothermal reservoir.

Treated wastewater: Municipal sewage/effluent that is treated at a publicly owned treatment works before being discharged.

Unappropriated surface water: Surface water that is not currently allocated to an existing water right.

Unidentified hydrothermal geothermal resources: Resources that are likely to exist but that have not been verified.

Water consumption: Water that is withdrawn from a source but not returned to its area of extraction in liquid form. Water may be consumed through evaporation, chemical reactions, incorporation into materials (e.g., in drilling muds and cement), or injection into nonaquifer geological formations (e.g., stimulation or reservoir makeup fluids).

Well stimulation: A variety of operations performed on a well to improve productivity. Water is the primary ingredient for most well stimulation activities. In EGS development, three types of stimulation are used: thermal, hydraulic, and chemical.

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APPENDIX A:

GEOTHERMAL ELECTRICITY GENERATION

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APPENDIX A:

GEOTHERMAL ELECTRICITY GENERATION

Three different types of geothermal systems were evaluated in this work: (1) conventional hydrothermal flash, (2) conventional hydrothermal binary, and (3) enhanced geothermal (EGS). Although Argonne National Laboratory (Argonne) has also evaluated geopressured geothermal systems (Clark et al. 2012), they were not re-evaluated in the current study because the resource and economic growth potential of geopressured systems are not as well characterized as the other technologies at this time. The previous results for geopressured systems are included and presented along with the results of the current study. Brief descriptions of the three types of systems evaluated in this analysis are provided below.

A.1 CONVENTIONAL HYDROTHERMAL FLASH SYSTEM

Hydrothermal flash systems typically rely upon geofluids above 182°C (360°F) to make electricity (DOI and USDA 2008). This assessment considered geofluid temperatures between 175 and 300°C (347 and 572°F). 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, and any liquid that remains in the tank can be flashed again in a second system to generate more electricity. Vapor from these systems is typically released to the atmosphere, while the condensate is returned to the geothermal reservoir through an injection well.

A.2 CONVENTIONAL HYDROTHERMAL BINARY SYSTEM

Geofluid temperatures suitable for binary-cycle power plants range between 74 and 182°C (165 and 360°F) (DOI and USDA 2008). This study considered temperatures between 150 and 185°C (302 and 365°F). 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, and, as a result, the heat transferred from the geofluid causes the working fluid to flash to vapor, which can drive a turbine to generate electricity. After flowing through a heat exchanger, the geofluid is reinjected to an underground reservoir. Because this is a closed-loop system, atmospheric emissions are minimal.

A.3 ENHANCED GEOTHERMAL SYSTEM

EGS can expand the electricity-generating capacity of geothermal resources by expanding existing fractures or creating new fractures to improve water circulation through a geothermal resource. These systems can be implemented in formations that are dryer and deeper than conventional geothermal resources (DOE 2008). Temperatures considered for this life cycle

analysis were between 175 and 225°C (347 and 437°F). Because of the different reservoir properties such as increased depths and temperatures, decreased reservoir permeability and porosity, and lower quantities of fluid within the reservoir, environmental impacts from EGSs can differ from those associated with conventional geothermal power plants.

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APPENDIX B:

ENHANCED GEOTHERMAL SYSTEM STIMULATION JOBS FROM THE LITERATURE

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TABLE B-1 EGS Stimulation Jobs from the Literature

Location	Well Name (if available)	Volume of Water Per Stimulation Event (m^3)	Geologic Formation Stimulated	Reservoir Size (if available)	Reference
Australia, Arowie Basin	Parlana 2	2,652	Metasediment and felsic porphry dolerite dykes	250–500 m^3	Beach Energy et al. 2010, 2011a,b
Australia, Cooper Basin	Habanero 1 (stimulated in 2003)	20,000	Granite	25,000–250,000 m^3	Asanuma et al. 2005,[a] INL 2006, Chen and Wyborn 2009[b]
Australia, Cooper Basin	Habanero 1 (stimulated in 2005)	20,000	Granite	40,000–400,000 m^3	Chen and Wyborn 2009
Australia, Cooper Basin	Habanero 2	7,000	Granite	4,000–40,000 m^3	Chen and Wyborn 2009
Australia, Cooper Basin	Habanero 3	2,200	Granite	2,000–20,000 m^3	Chen and Wyborn 2009
Australia, Cooper Basin	Proposed stimulation	30,000	Granite	40,000,000–400,000,000 m^3	Geodynamics 2010, Chen and Wyborn 2009[c]
France, Soultz-sous-Forêts	GPK3	34,000	Granite	2 km^3	Michelet and Toksöz 2007, McClure and Horne 2012, Valley 2007[d], Schindler et al. 2010
France, Soultz-sous-Forêts	GPK2 (stimulated in 1996)	58,000	Granite	2 km^3	INL 2006, Cordon and Driscoll 2008, McClure and Horne 2012, Valley 2007
France, Soultz-sous-Forêts	GPK2 (stimulated in 2000)	23,400	Granite	2 km^3	INL 2006, Cordon and Driscoll 2008, McClure and Horne 2012, Valley 2007, Schindler et al. 2010

TABLE B-1 (Cont.)

Location	Well Name (if available)	Volume of Water Per Stimulation Event (m^3)	Geologic Formation Stimulated	Reservoir Size (if available)	Reference
France, Soultz-sous-Forêts	GPK 4 (unknown stimulation date)	9,300	Granite	2 km^3	Schindler et al. 2010
France, Soultz-sous-Forêts	GPK 4 (unknown stimulation date)	123,000	Granite	2 km^3	Schinler et al. 2010
Germany	KTB Borehole (stimulated in 2000)	4,000	Paragneisses and metabasites		Shapiro et al. 2006[a]
Germany	KTB Borehole (stimulated in 2004 to 2005)	84,600	Paragneisses and metabasites		Shapiro et al. 2006[a]
Germany	KTB Borehole (stimulated in 1994)	200	Paragneisses and metabasites		Zoback and Harjes 1997[a]
Germany, Landau	GtLa2	4,600	Granite		Schindler et al. 2010
Germany, Landau	GtLa2	6,600	Granite		Schindler et al. 2010
Germany, Bad Urach	Unknown well	100	Gneiss		Stober 2011[a]
Germany, Bad Urach	Unknown well	5,600	Gneiss		Stober 2011[a]
Germany, Groß Schönebeck	GtGrSk4/05 volcanic layer	13,170	Andesite		Zimmermann et al. 2009
Germany, Groß Schönebeck	GtGrSk4/05 sandstone layer	250	Sandstone		Zimmermann and Reinicke 2010
Germany, Horstberg	Horstberg Z 1	20,000	Sandstone		INL 2006

TABLE B-1 (Cont.)

Location	Well Name (if available)	Volume of Water Per Stimulation Event (m^3)	Geologic Formation Stimulated	Reservoir Size (if available)	Reference
Hypothetical	Inferred in economic model	20,000			Murphy et al. 1985
Hypothetical	Proposed stimulation	29,500			Cordon and Driscoll 2008
Hypothetical	Stimulation proposed in referenced document	4,425			Cordon and Driscoll 2008
Japan, Ogachi	OGC-2 (stimulated in 1995)	4,300	Granodiorite	140,000–8,000,000 m^3	Kitano et al. 2000, INL 2006[e]
Japan, Ogachi	OGC-1 (stimulated in 1995)	3,400	Granodiorite		Kitano et al. 2000, INL 2006[e]
Japan, Ogachi	OGC-1 (stimulated in 1992)	5,500	Granodiorite		Kitano et al. 2000, INL. 2006[e]
Japan, Ogachi	OGC-1 (stimulated in 1991)	10,000	Granodiorite		Kitano et al. 2000, INL 2006[e]
Japan, Hijiori	SKG-2	2,000	Volcanic caldera		INL 2006
Japan, Hijiori	HDR-1	2,115	Volcanic caldera		INL 2006
Sweden, Fjallabacka	FjbI	400	Granite		Evans et al, 2012[a], INL. 2006[e]
Switzerland, Basel	Basel 1 Well	11,500	Granite		Häring et al. 2008[a]
USA, Newberry Volcano, Oregon	NWG 55-29	90,840	Volcanic rock		Cladouhos et al.2012

TABLE B-1 (Cont.)

Location	Well Name (if available)	Volume of Water Per Stimulation Event (m^3)	Geologic Formation Stimulated	Reservoir Size (if available)	Reference
USA, Baca Project Area, New Mexico	Baca 23	1,215	Volcanic tuffs		Morris and Bunyak1981
USA, Baca Project Area, New Mexico	Baca 20	1,389	Volcanic tuffs		Morris and Bunyak 1981
USA, Desert Peak, Nevada	27-15	13,250	Rhyolite		Chabora et al. 2012 and Chabora, 2013 personal communication

[a] As referenced in McClure and Horne (2012).

[b] A 12,000-m^3 volume referenced in Xu et al. (2012) was not included since the value conflicts with Chen and Wyborn (2009), Asanuma et al. (2005), and INL (2006).

[c] Chen and Wyborn (2009) reference a final stimulation zone of 4 km^2 (2.2 mi^2) in extent with a thickness in the 10- to 100-m (3- to 30-ft) range.

[d] Valley (2007) reports on the reservoir size.

[e] INL (2006) reports on the reservoir size.

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APPENDIX C:

CHEMICAL STIMULATION

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APPENDIX C:

CHEMICAL STIMULATION

Table C-1 lists the range of chemicals used during well stimulation activities. Different chemicals are typically used according to geology. Hydrochloric acid (HCl) is used to treat calcium-containing formations such as limestone and dolomite. Carbonate reservoirs are particularly susceptible to HCl and its derivative, muriatic acid. Mixtures of HCl and hydrofluoric acid (HF) are used in sandstone acidizing operations. Sandstone acidizing requires a three-step procedure. A preflush is performed with a 10% HCl solution with the objectives of displacing formation brine away from the wellbore and dissolving and removing as much of the calcerous material as possible. The mainflush, a mixture of 12% HCL and 3% HF (often called regular mud acid or RMA), is prepared by dissolving ammonium bifluoride in HCl, and is then pumped into the well. As a final step, the overflush, which consists of HCl, potassium chloride (KCl), ammonium chloride (NH_4Cl), or fresh water, is used to displace the nonreacted RMA (and any reaction products) into the formation and away from the wellbore (Portier et al. 2009; Zimmermann et al. 2011).

TABLE C-1 Chemicals Used during Well Stimulation Activities

Chemical	Purpose
Acids	
HCl	Acidizing calcaerous formations
RMA: HCl and HF mixture with HCl varying from 6 to 12% and HF varying from 0.5 to 3%. Typical source ingredients are ammonium bifluoride in HCL.	Acidizing sandstone formations, dissolution of drilling muds and clays
RMA using phosphonic acid complex as a substitute for HCl.	Acidizing naturally fractured volcanic formations
Acetic acid (injection of solutions of methyl acetate hydrolyzes to acetic acid)	Better permeation of acidizing effect
Chloroacetic acid	Better permeation of acidizing effect
Formic acid	Better permeation of acidizing effect
Sulfamic acid	Better permeation of acidizing effect
Fluoroboric acid	Better permeation of acidizing effect
Fluoroaluminic acid	Better permeation of acidizing effect
Hexa-fluoro-phosphoric acid	Better permeation of acidizing effect
Organosulfonic acid	Better permeation of acidizing effect
Organic clay acid for high-temperature (OCA-HT): citric, hydrofluoric, and borofluoric acids and NH_4Cl.	Better permeation of acidizing effect
Gelling agents (polymers and surfactants),	Better permeation of acidizing effect
emulsified solutions of aqueous acid in oil;	Better permeation of acidizing effect
acids dissolved in a solvent (e.g., alcohol and gel)	Better permeation of acidizing effect
Chelating Agents	.
Ethylenediaminetetraacetic acid (EDTA)	Formation cleanup, especially in formations that could be damaged by acids; dissolution of iron, calcium, magnesium and aluminum; lower dissolution rate in calcium formations means the chelating agent can penetrate further into the formation
Nitrilo-triacetic acid (NTA)	Formation cleanup, especially in formations that could be damaged by acids; dissolution of iron, calcium, magnesium and aluminum; lower dissolution rate in calcium formations means the chelating agent can penetrate further into the formation
Sodium sulfophthalate (SPA)	Formation cleanup, especially in formations that could be damaged by acids; dissolution of iron, calcium, magnesium and aluminum; lower dissolution rate in calcium formations means the chelating agent can penetrate further into the formation
Hydroxyethylenediaminetriacetic acid (HEDTA)	Formation cleanup, especially in formations that could be damaged by acids; dissolution of iron, calcium, magnesium and aluminum; lower dissolution rate in calcium formations means the chelating agent can penetrate further into the formation

TABLE C-1 (Cont.)

Chemical	Purpose
Chelating Agents (Cont.)	.
Hydroxyethyliminodiacetic acid (HEIDA)	Formation cleanup, especially in formations that could be damaged by acids; dissolution of iron, calcium, magnesium and aluminum; lower dissolution rate in calcium formations means the chelating agent can penetrate further into the formation
Bases	
Sodium carbonate	Dissolution of wellbore silica and near-wellbore formation silicates.
Sodium hydroxide	Dissolution of wellbore silica and near-wellbore formation silicates.
Ammonia	Dissolution of wellbore silica and near-wellbore formation silicates.
Inorganics	
Potassium chloride	
Chlorine solutions	
Tracers	
Sodium fluorescein tracer	Tracer
1,6-napthalene disulfonate (conservative tracer)	Tracer
Safranin T (reactive tracer)	Tracer
1,3,5-napthalene trisulfonate	Tracer
Diverters	
BioVertTM, a polymer of lactic acid, or PLA	Interval isolation
Additives	
Corrosion inhibitors	Corrosion inhibition
Proppants	Keeping fractures open

Sources: Portier et al. (2009); Chabora et al. (2012); Chen and Wyborn (2009); Zimmermann et al. (2011); Malate et al. (1998); Cladouhos et al. (2012).

To maximize acidizing compound effectiveness, mixtures are used that penetrate deep into the formation and then form the active acidizing compound. The longer reaction time allows greater penetration of the formation. The chemicals that retard the desired acidification reaction can involve weak organic acids like fluoroboric and fluoroaluminic acids. Other strategies that can be used include creating acid systems in gelling agents, emulsified solutions of acid in oil, and acids dissolved in solvent. Chelating agents such as ethylenediaminetetraacetic acid (EDTA) can also be used for formation cleanup (Portier et al. 2009).

RMA and nitrilotriacetic acid have been used to treat conventional and EGS geothermal wells. Acid stimulations performed by using preflush, main flush, and overflush have been used to stimulate geothermal wells. Naturally fractured volcanic formations can withstand concentrated HF solutions in the main flush stage (e.g., 10% HCL or 5% HF). In comparison to the oil and gas industry, additives, including corrosion inhibitors and inhibitor intensifiers, may be needed for elevated temperatures associated with a geothermal environment (Portier et al. 2009).

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APPENDIX D:

ABOVEGROUND OPERATIONAL WATER CONSUMPTION IN GEOTHERMAL POWER PLANTS

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TABLE D-1 Geothermal Power Plant Geofluid Production and Injection and State Permit Data[a]

				Reported Production vs. Injection			NV Permit Data	
Plant Name	Plant Type	Cooling System Type	Rated Capacity (MW)	Production (gal/day)	Injection (gal/day)	Difference (gal/day)	Permitted Production (gal/day)	Permitted Loss (gal/day)
Beowawe	Flash	Water	16.6	6,075,000	5,018,000	(1,057,000)	7,491,000	1,063,000
Desert Peak 1	Flash	Water	12.5	2,707,000	2,088,000	(619,000)	5,166,000	1,033,000
Dixie Valley	Flash	Water	62	13,919,000	10,517,000	(3,402,000)	20,182,000	5,377,000
Salton Sea	Flash	Water	336	72,256,000	59,016,000	(13,240,000)		
Brady Hot Springs	Binary and flash	Air and water	21.1	11,426,000	8,557,000	(2,869,000)	17,437,000	3,814,000
East Mesa	Binary and flash	Air and water	79	50,434,000	48,358,000	(2,076,000)		
Heber	Binary and flash	Air and water	85	35,386,000	33,126,000	(2,260,000)		
Soda Lake	Binary	Hybrid	26.1	6,125,000	6,081,000	(44,000)	6,458,000	323,000
Desert Peak 2	Binary	Hybrid	11	228,000	166,000	(62,000)		
Steamboat Complex	1 Flash, 6 binary	Air	89	55,104,000	56,380,000	1,276,000		
Stillwater	Binary	Air	21	7,416,000	7,236,000	(180,000)	13,949,000	1,397,000
Casa Diablo	Binary	Air	40	17,370,000	16,955,000	(415,000)		
Wabuska	Binary	Cooling ponds, not reinjected	2.2	3,744,000	0	(3,744,000)	7,750,000	7,750,000

[a] All fluid volumes in this table are geofluid volumes.

TABLE D-2 Aboveground Operational Water Consumption in Geothermal Power Plants

Plant Name	Type	Cooling	Location	Water Consumption (gal/ kWh)	Notes	Source
Cooling Water						
Geysers - Calpine	Dry Steam	Water	California	1.126	Municipal wastewater, condensate, and surface water all used for reservoir makeup.	Calpine 2012
Coso Hay Ranch/China Lake	Flash	Water	California	0.73	Groundwater, makeup injection for loss from cooling; average annual consumption.	BLM and U.S. Navy 2008
Salt Wells-Vulcan	Flash	Water	Nevada	3.79	Estimated water consumption, could be geofluid or fresh makeup water.	BLM 2011a
Dixie Valley	Flash	Water	Nevada	2.17	Reinjection program started in 2002.	NDWR 2012
Modeled System	Flash	Water		2.70	System modeled in Geothermal Electricity Technology Evaluation Model (GETEM), assumes all lost geofluid replaced through reinjection.	Clark et al. 2012
Blue Mountain	Binary	Water	Nevada	2.42	Estimated, would be groundwater if binary or condensate if flash plant.	BLM 2007
East Mesa	4 Binary, 2 flash	Water	California	4.86	Exact generation unclear. Source mentions 73 MW in one location and 50 MW in another. Cooling water is taken from surface water from local irrigation district.	Environmental Management Associates 2006
Tuscarora	Binary	Water	Nevada	3.79	From fresh water wells, wet cooling towers with 3.2X concentration factor.	DOE 2011

TABLE D-2 (Cont.)

Plant Name	Type	Cooling	Location	Water Consumption (gal/ kWh)	Notes	Source
Cooling Water (Cont.)						
Patua	Binary	Water	Nevada	4.50	Groundwater for wet-cooled system, no significant water required for air cooled system.	BLM 2010a
Salt Wells-Vulcan	Binary	Water	Nevada	4.55	For wet cooling.	BLM 2011a
Oregon Institute of Technology	Binary	Water	Oregon	1.50	Estimated evaporative loss, makeup from fresh groundwater well.	MHA 2008
San Emidio	Binary	Water	Nevada	2.76	Based on new permits for consumptive use in 2010 coinciding with revamping and expanding the plant which opened in 2012 with net generation of 8.6 MW.	NDWR 2012
Salt Wells - Ormat	Binary	Hybrid	Nevada	1.10	Range of 2,500–3,500 gpm when operating wet cooling, 1.1 gal/kwh assuming 3 months of operation, 1.5 assuming 4 months of operation.	BLM 2011a
Coyote Canyon	Flash	Hybrid	Nevada	0.32	Exact plant configuration not determined, water consumption assuming a flash system with hybrid cooling.	BLM 2010b
McGinness	Binary	Hybrid	Nevada	1.72	Hybrid cooling, 50% fresh water, 50% geofluid, only fresh water included.	BLM 2011b
Soda Lake	Binary	Hybrid	Nevada	0.57	Cool working fluid in cooling towers, for dust suppression, drilling equipment maintenance, etc.	NDWR 2012

TABLE D-2 (Cont.)

Plant Name	Type	Cooling	Location	Water Consumption (gal/ kWh)	Notes	Source
Cooling Water (Cont.)						
Theoretical Plant	Binary	Hybrid		0.74	Model results showing water consumption for hybrid system that increases summer output by ~15%.	Kozubal and Kutscher 2003
Water for Other Uses						
Dixie Valley	Flash	Water	Nevada	0.24	Maximum consumption for drilling and plant operations.	NDWR 2012
Steamboat Complex	6 binary, 1 flash	Air	Nevada	0.07	Fresh surface water consumption for enhanced cooling and other industrial uses. Much of water being used for hybrid cooling tests at some of the binary plants.	NDWR 2012
Jersey Valley	Binary	Air	Nevada	0.001	Facility operations, mostly washing and bathrooms.	DOE 2011
Coyote Canyon	Flash or Binary	Hybrid or Air		0.03	Maximum noncooling water consumption (dust control, maintenance, domestic water).	BLM 2010b
Cooper Creek EGS-Geodynamics	Binary (EGS)	Air	Australia	0.12	Estimated ongoing water requirements for plant, sourced from local groundwater.	Geodynamics 2011
Telephone Flat	Flash	Water	California	0.006	Does not include loss of geofluid. Fresh water consumption for other plant uses.	Kagel et al. 2005
Salton Sea (all plants)	Flash	Water	California	0.06	Total fresh groundwater use for whole complex (from Appendix B).	CEC 2008

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APPENDIX E:

WATER DEMAND MAPS

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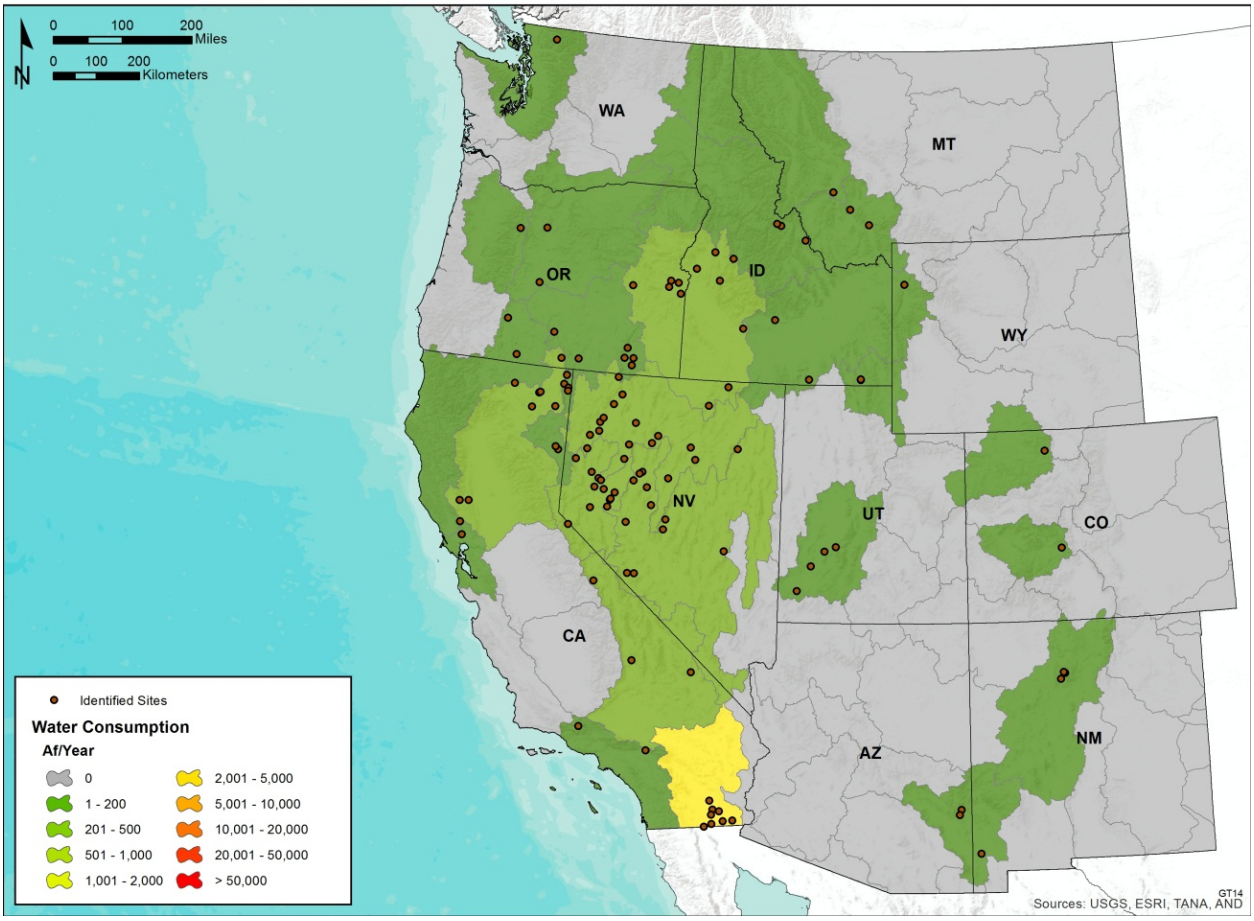

FIGURE E-1 All Identified Geothermal Resources

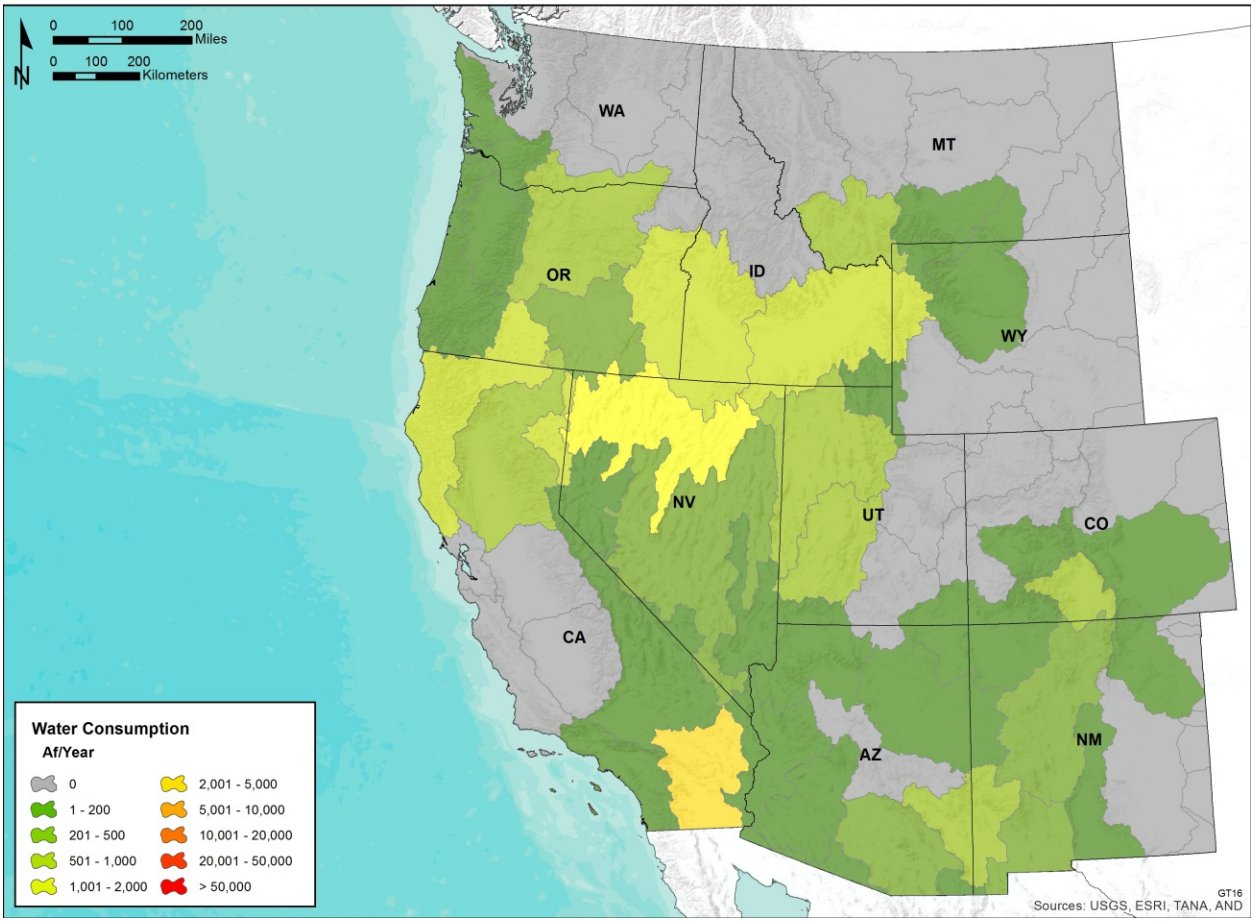

FIGURE E-2 All Unidentified Geothermal Resources

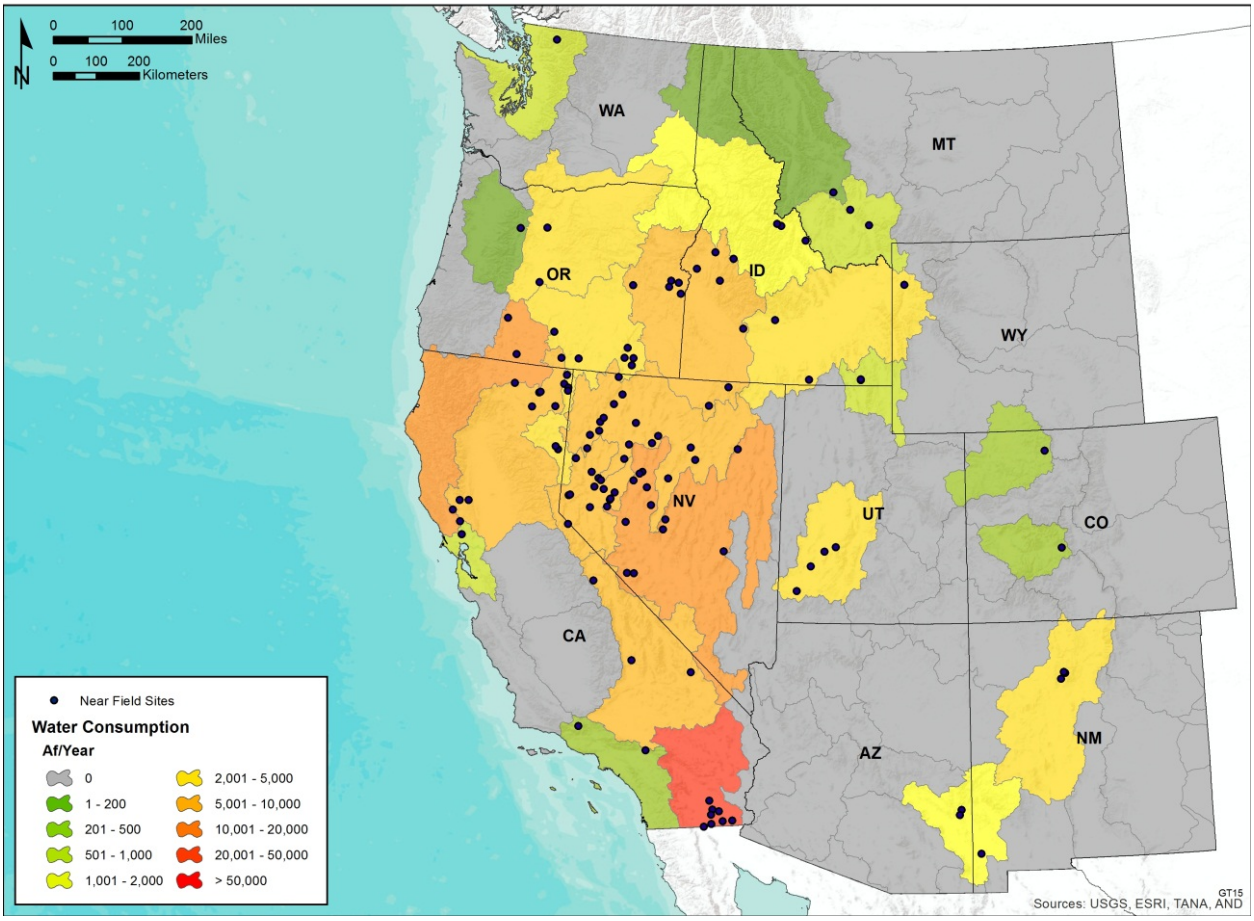

FIGURE E-3 All Near-Field Geothermal Resources

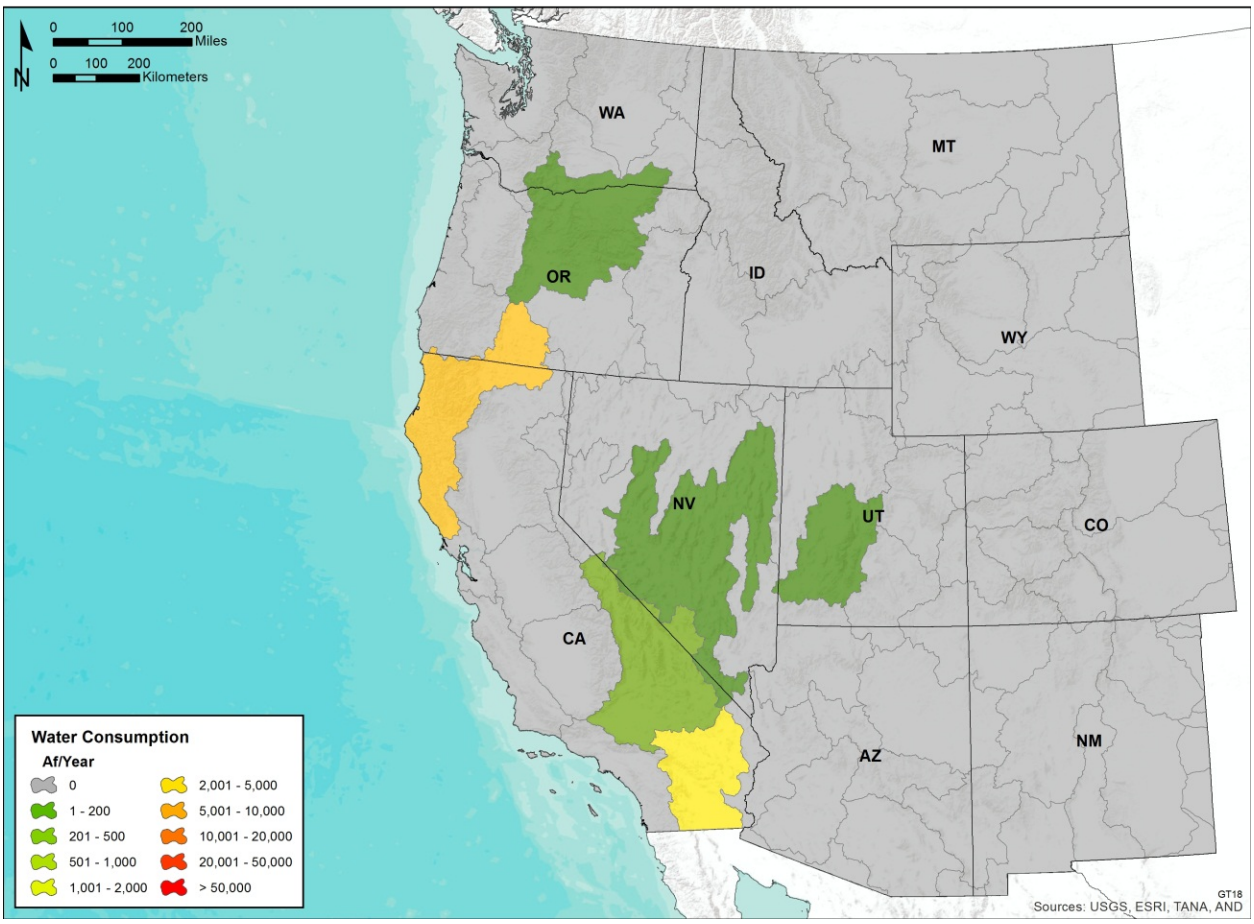

FIGURE E-4 All Resources under $0.05/kWh, Target Cost Curve

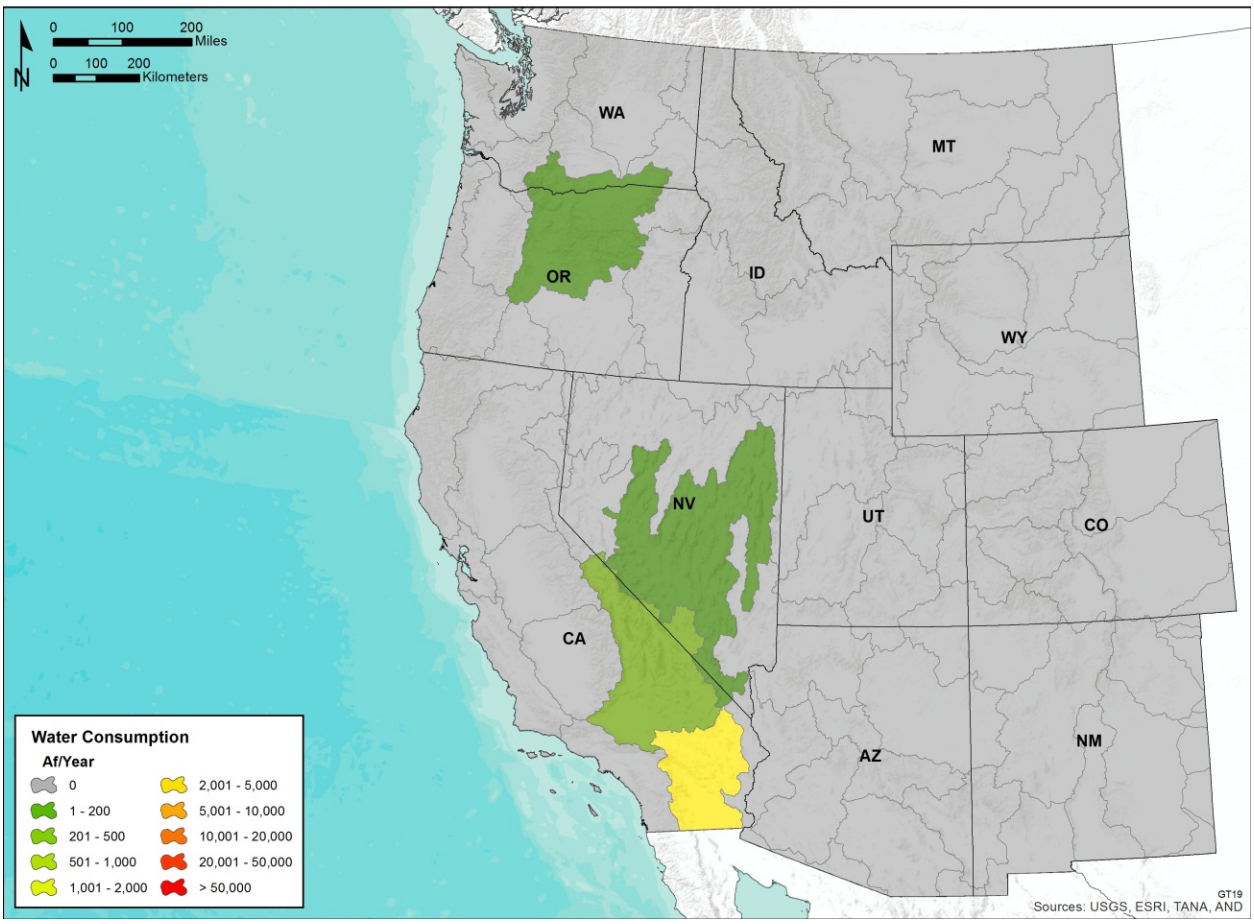

FIGURE E-5 All Resources under $0.05/kWh, Base Cost Curve

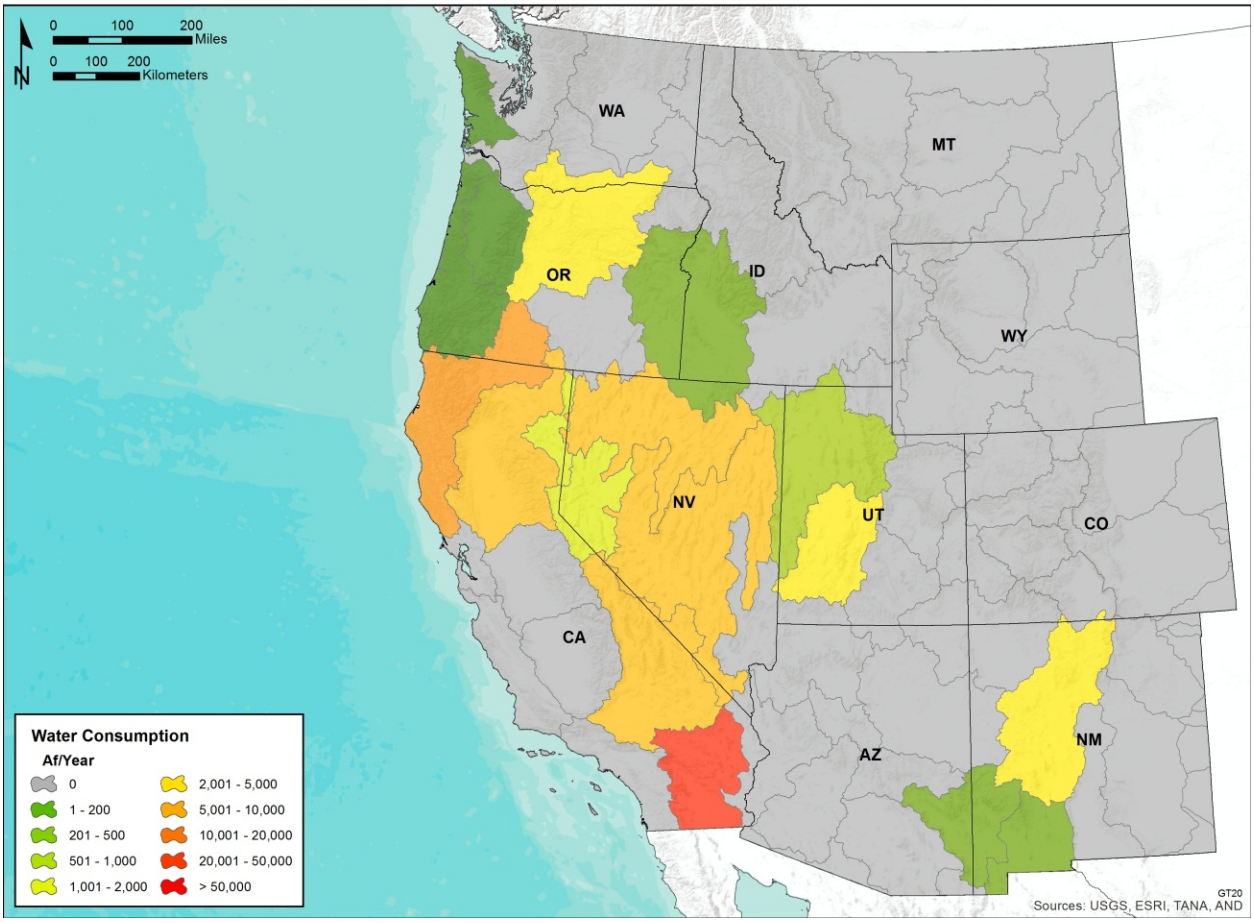

FIGURE E-6 All Resources under $0.10/kWh, Target Cost Curve

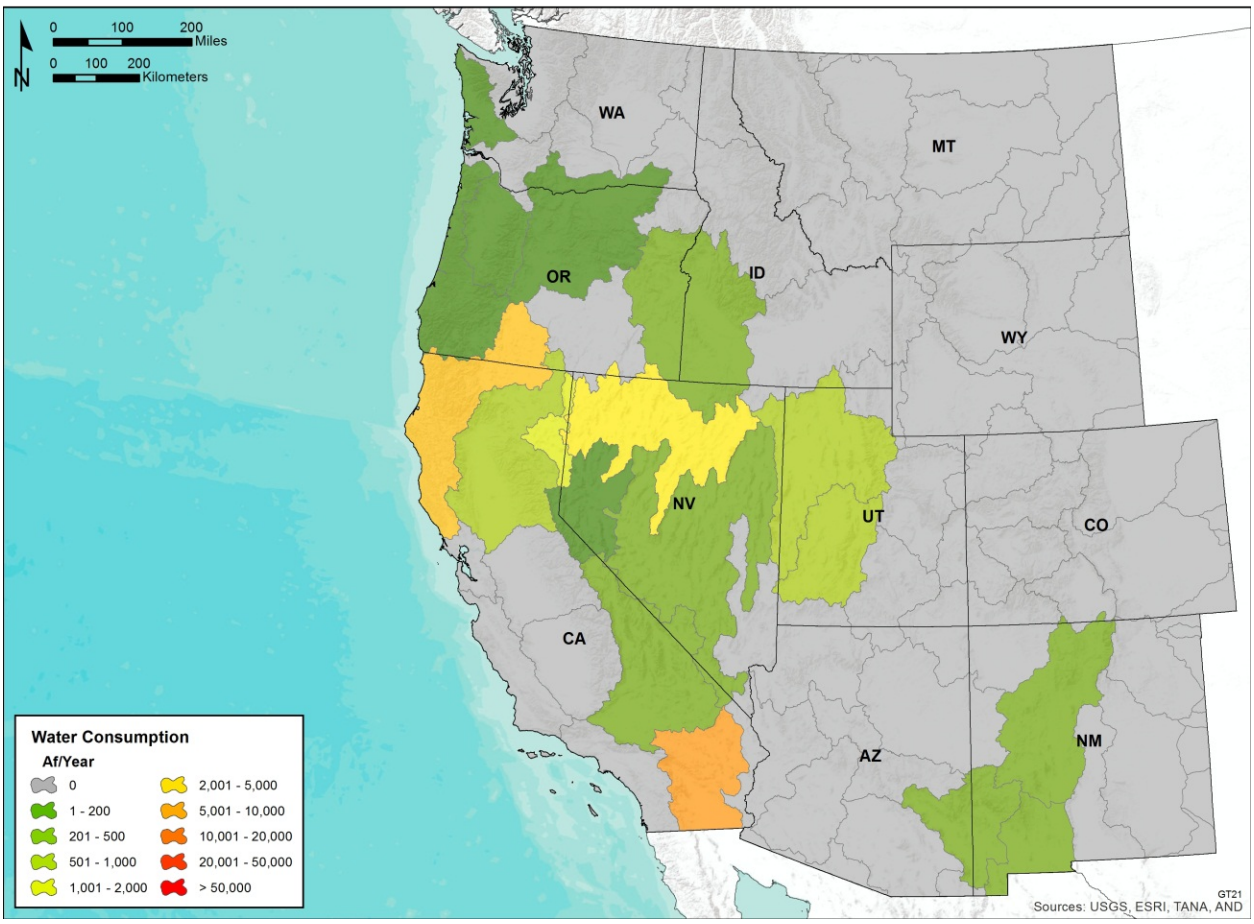

FIGURE E-7 All Resources under $0.10/kWh, Base Cost Curve

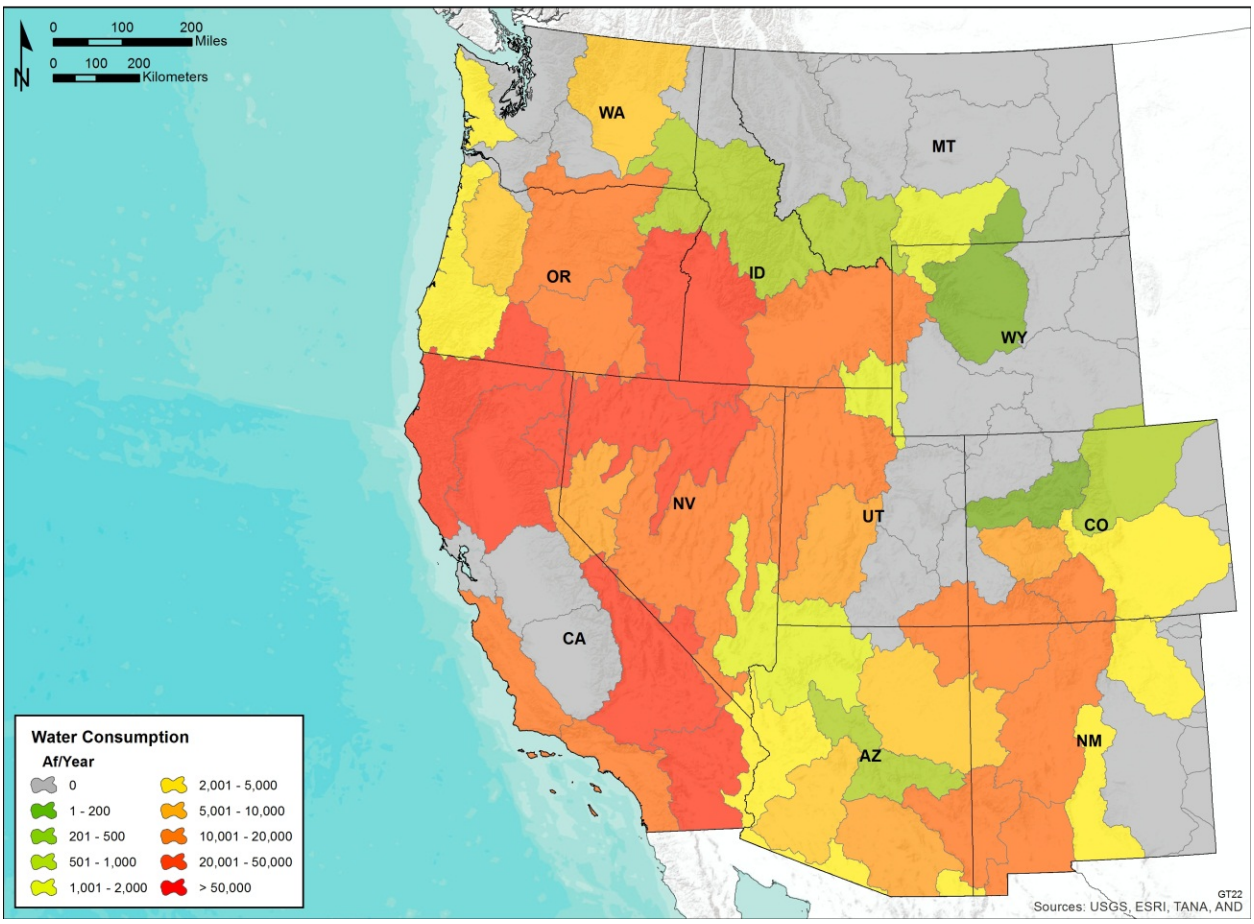

FIGURE E-8 All Resources under $0.15/kWh, Target Cost Curve

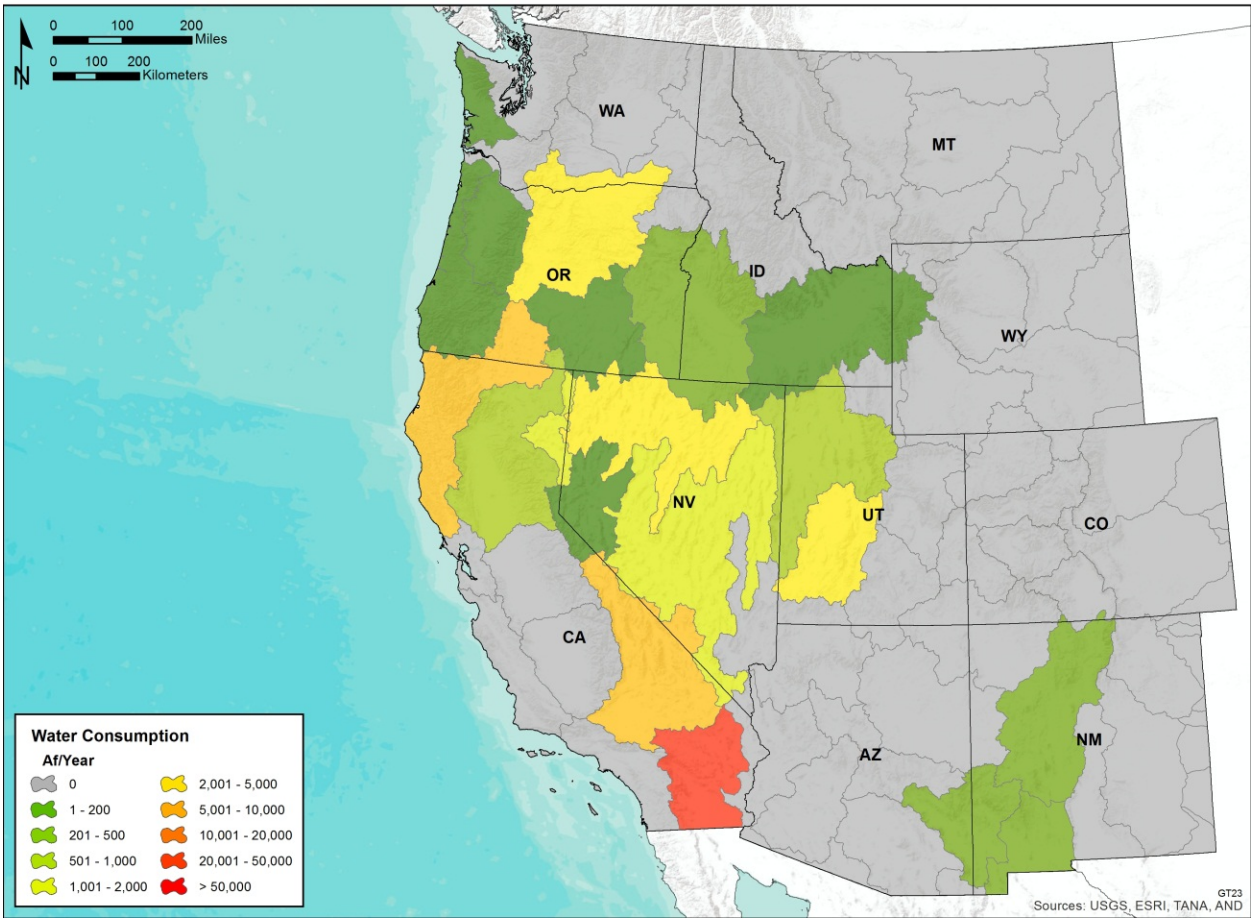

FIGURE E-9 All Resources under $0.15/kWh, Base Cost Curve

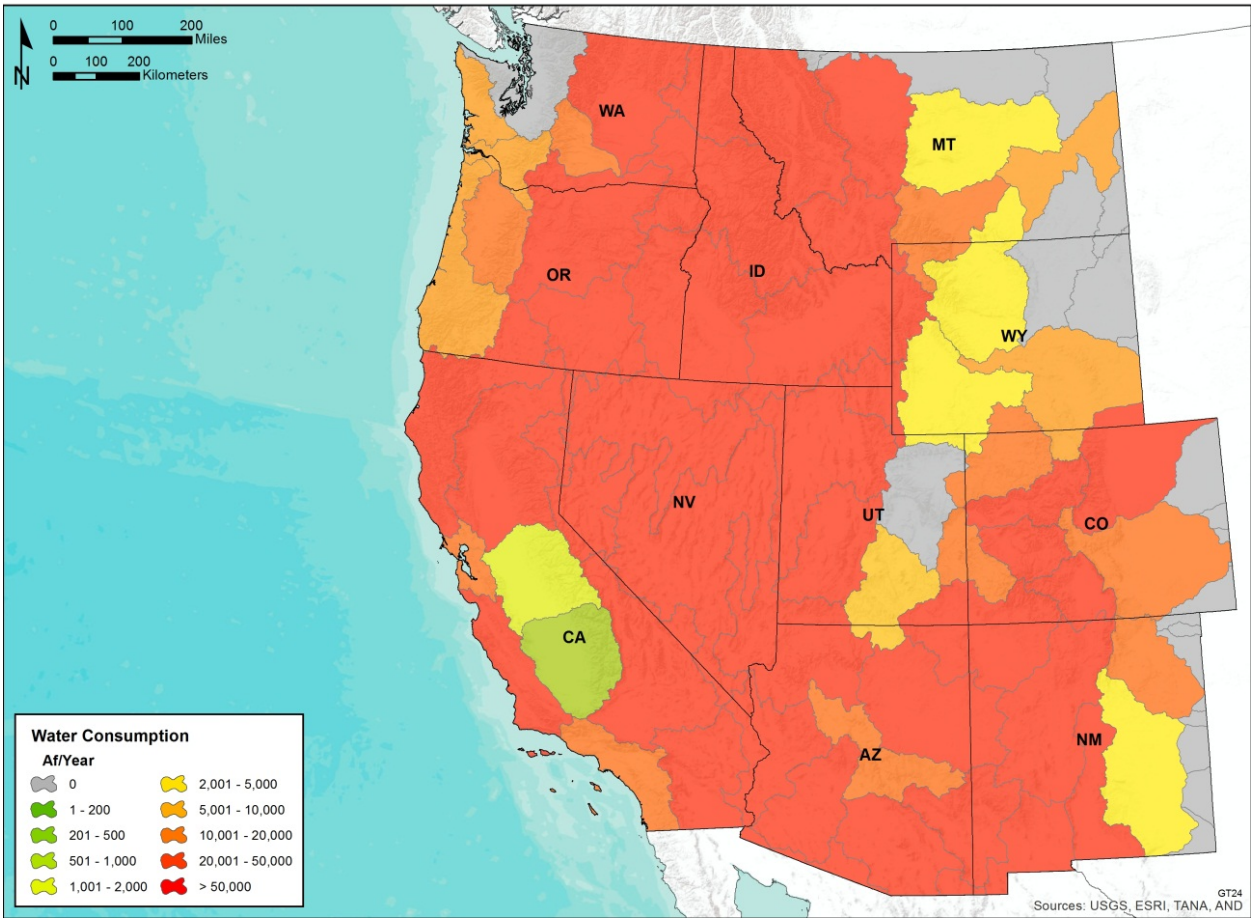

FIGURE E-10 All Resources under $0.20/kWh, Target Cost Curve

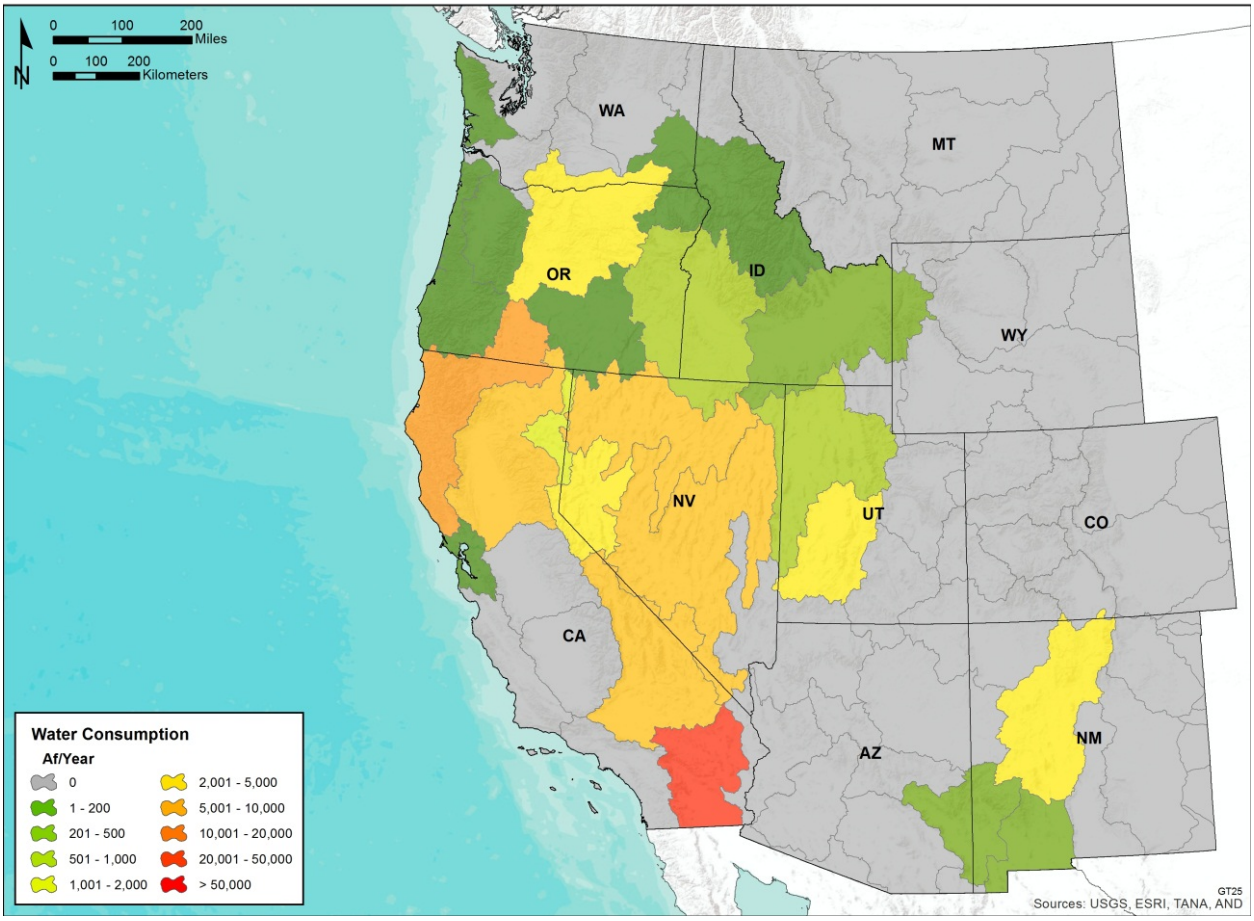

FIGURE E-11 All Resources under $0.20/kWh, Base Cost Curve

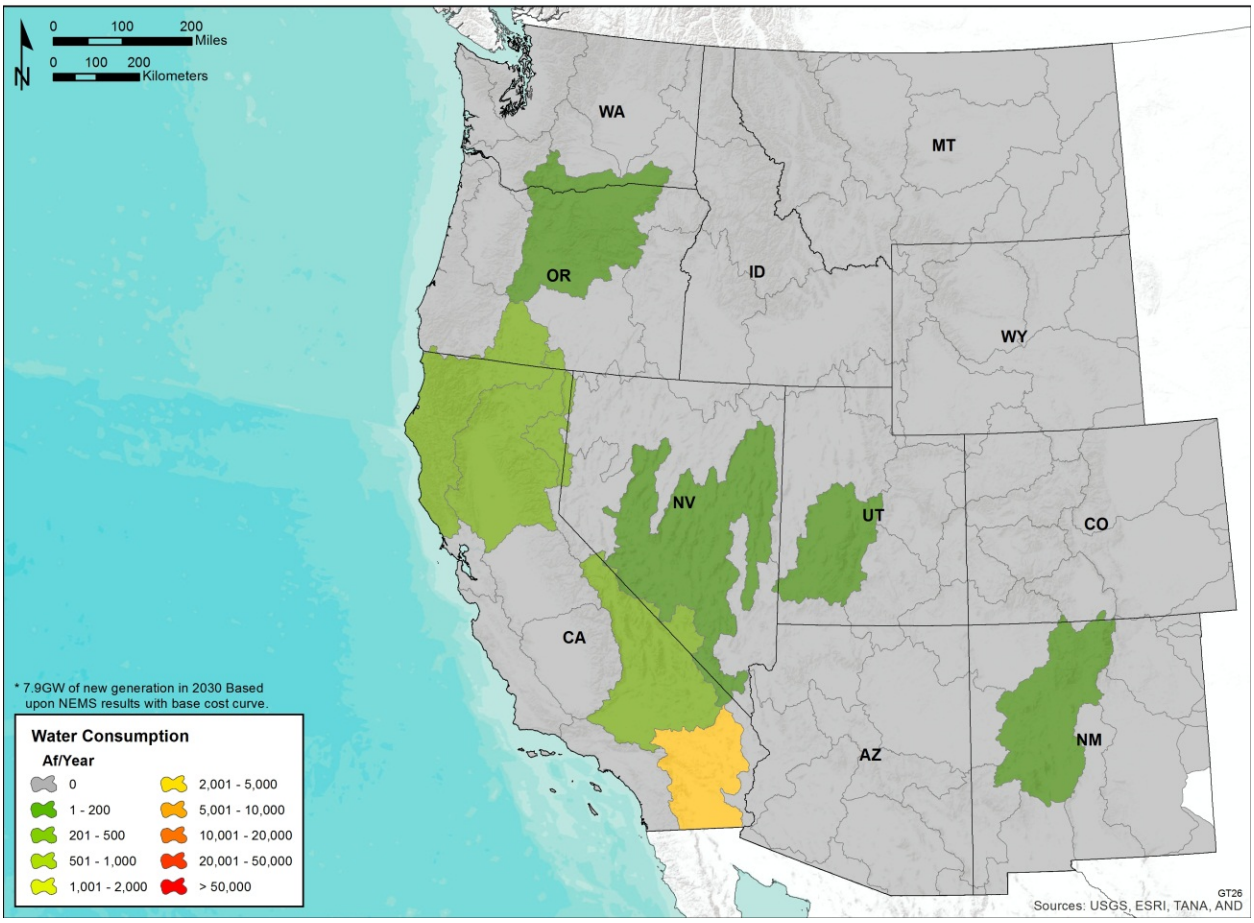

FIGURE E-12 NEMS-GPRA 2030 Growth Scenario, Base Cost Curve

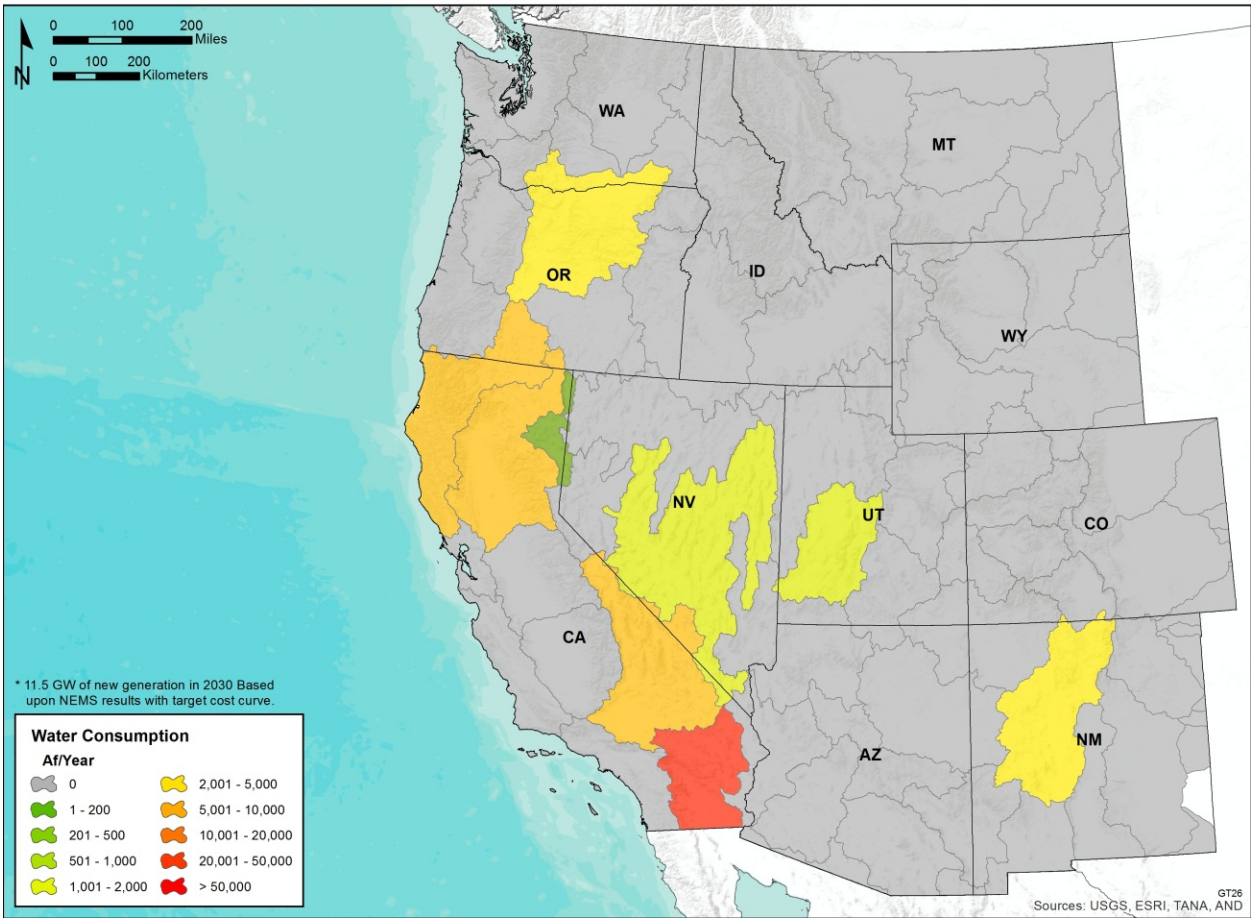

FIGURE E-13 NEMS-GPRA 2030 Growth Scenario, Target Cost Curve

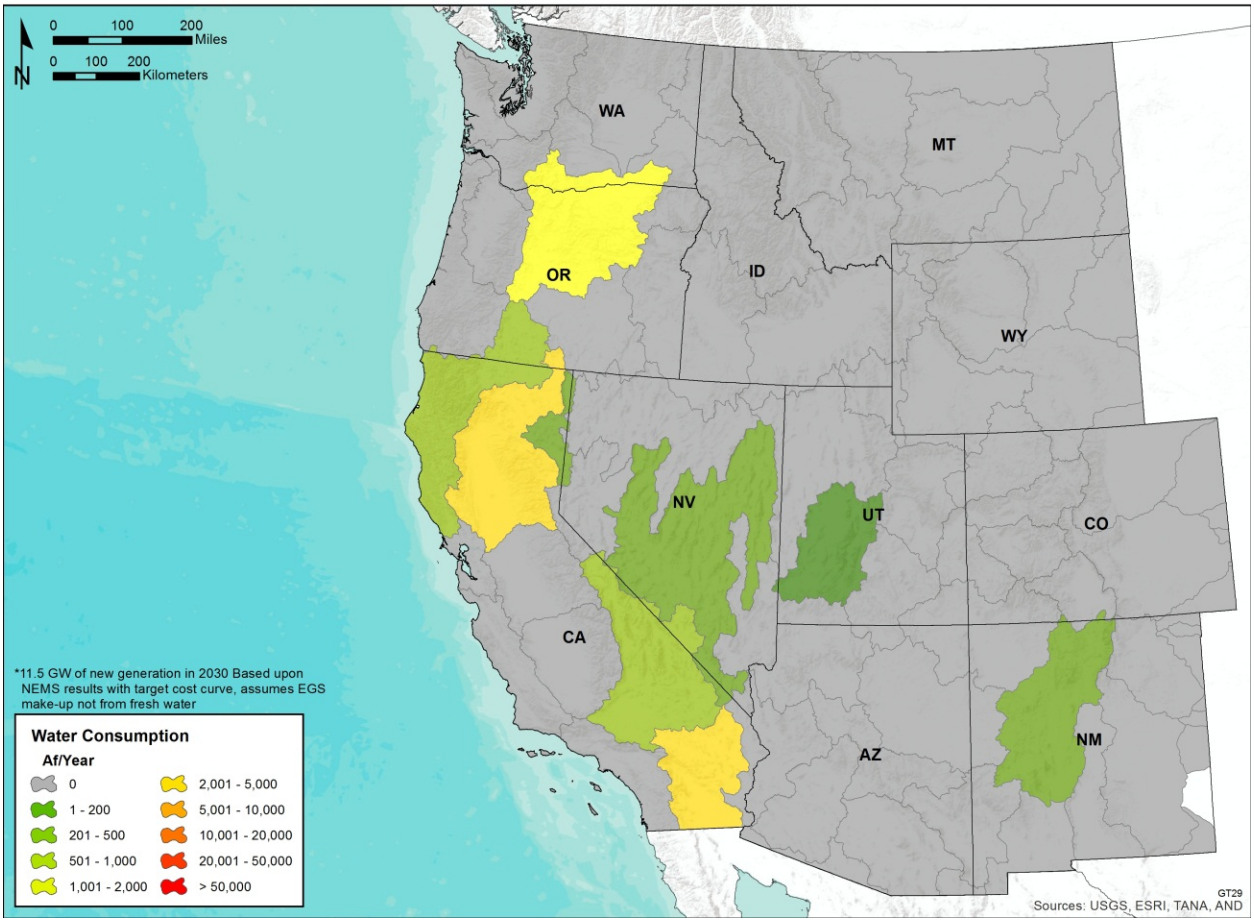

FIGURE E-14 NEMS-GPRA 2030 Growth Scenario, Target Cost Curve, No EGS Reservoir Loss

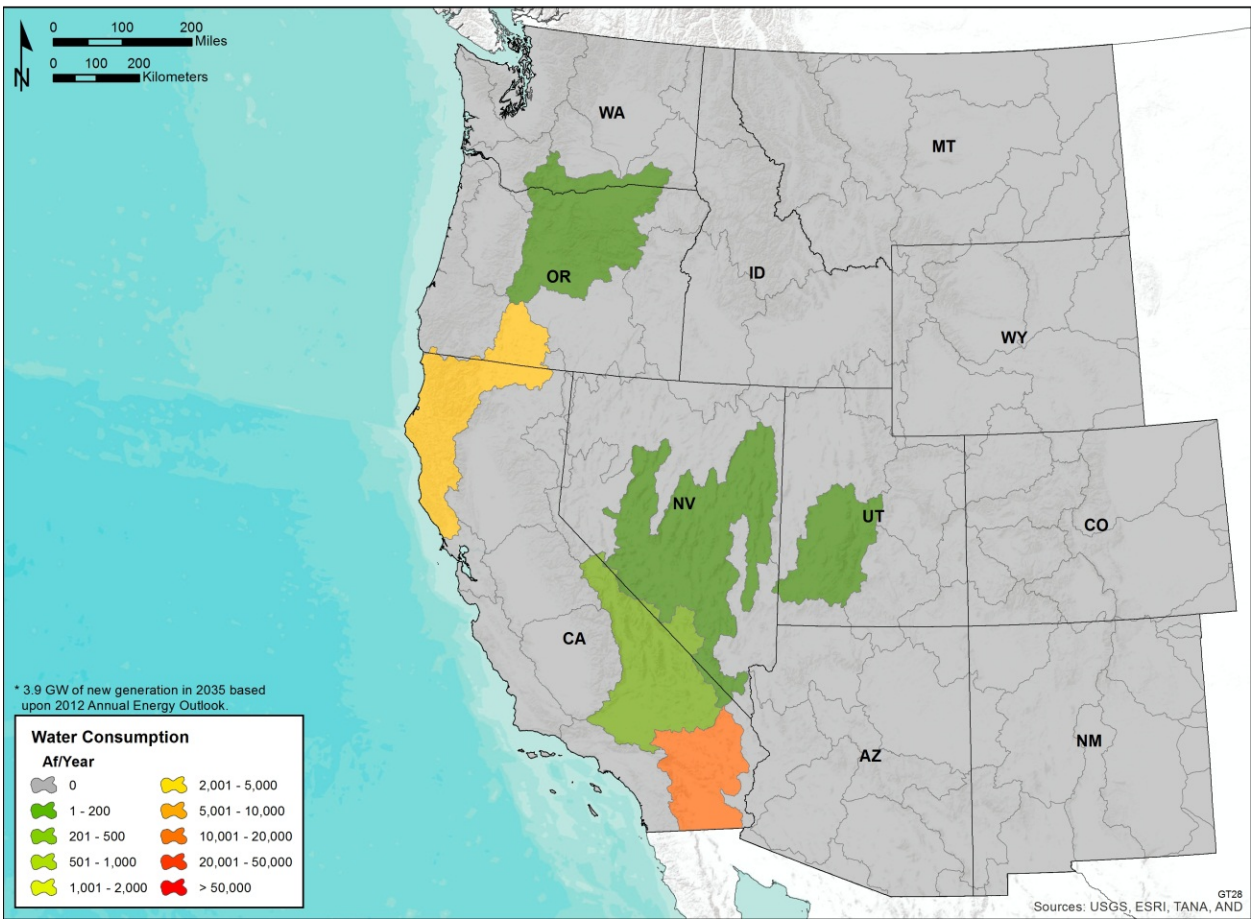

FIGURE E-15 EIA Annual Energy Outlook 2012 2035 Growth Scenario, Target Cost Curve

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APPENDIX F:

WATER AVAILABILITY MAPS

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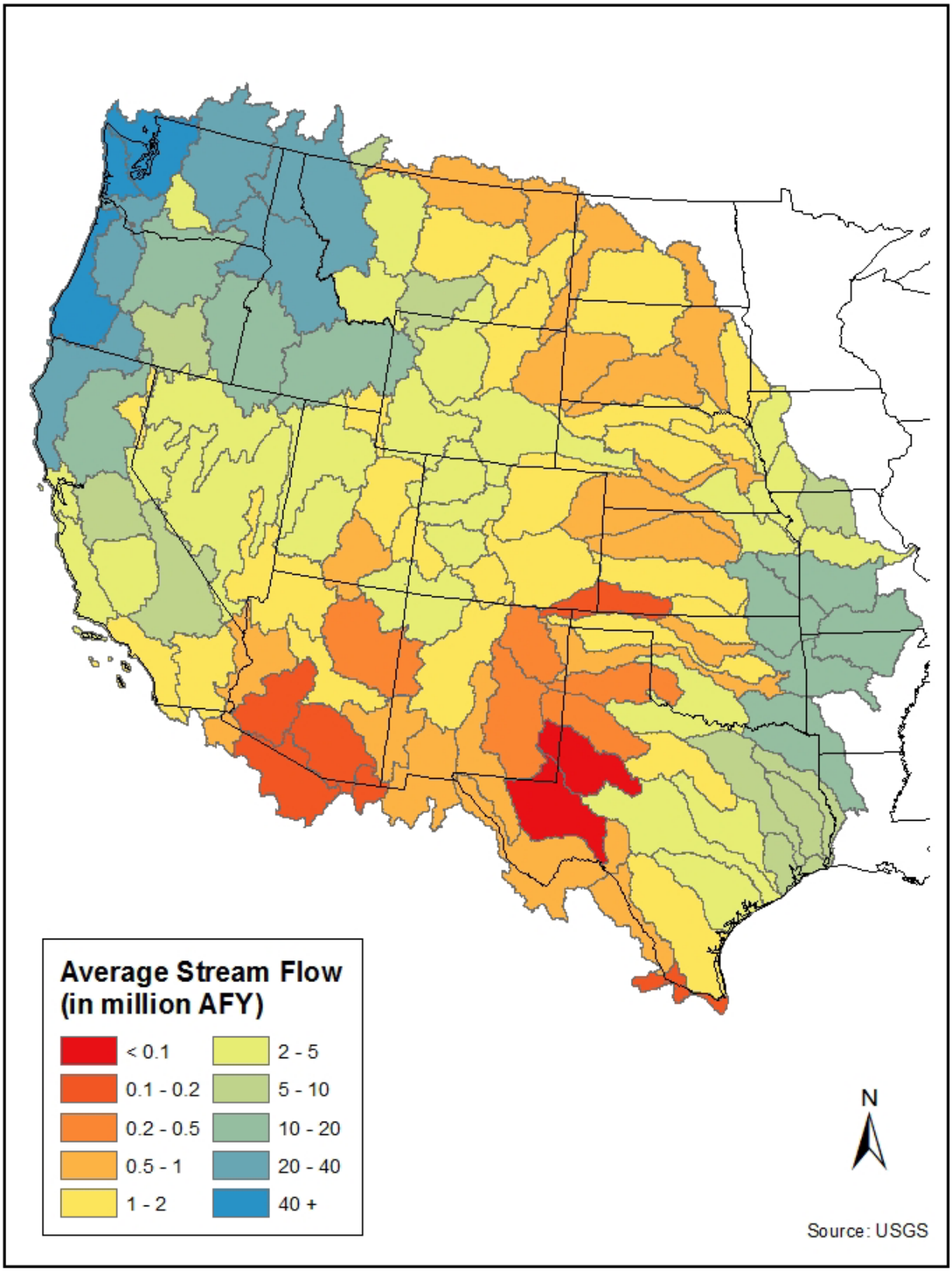

FIGURE F-1 Average Streamflow, 1950–2010

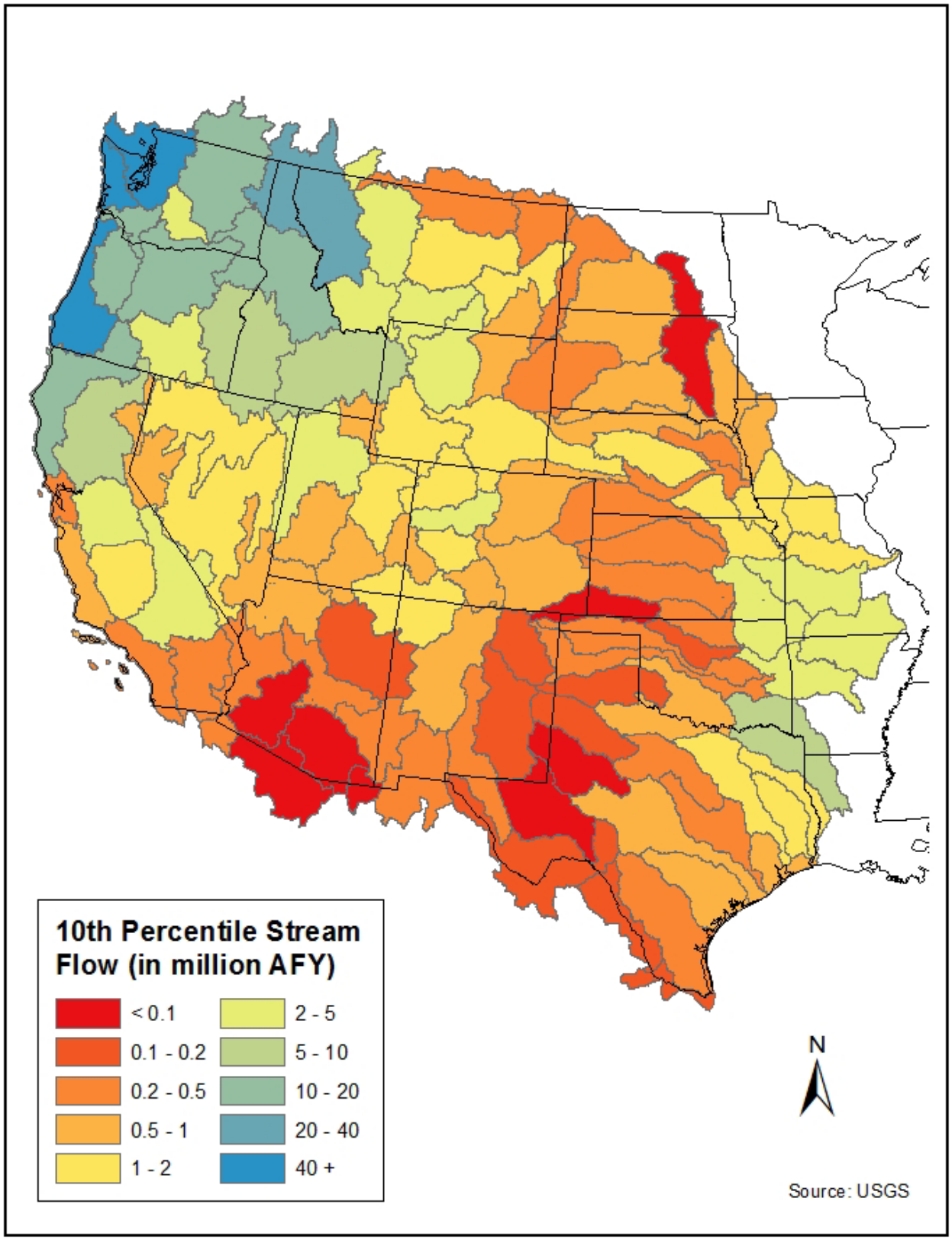

FIGURE F-2 Tenth Percentile Streamflow, 1950–2010

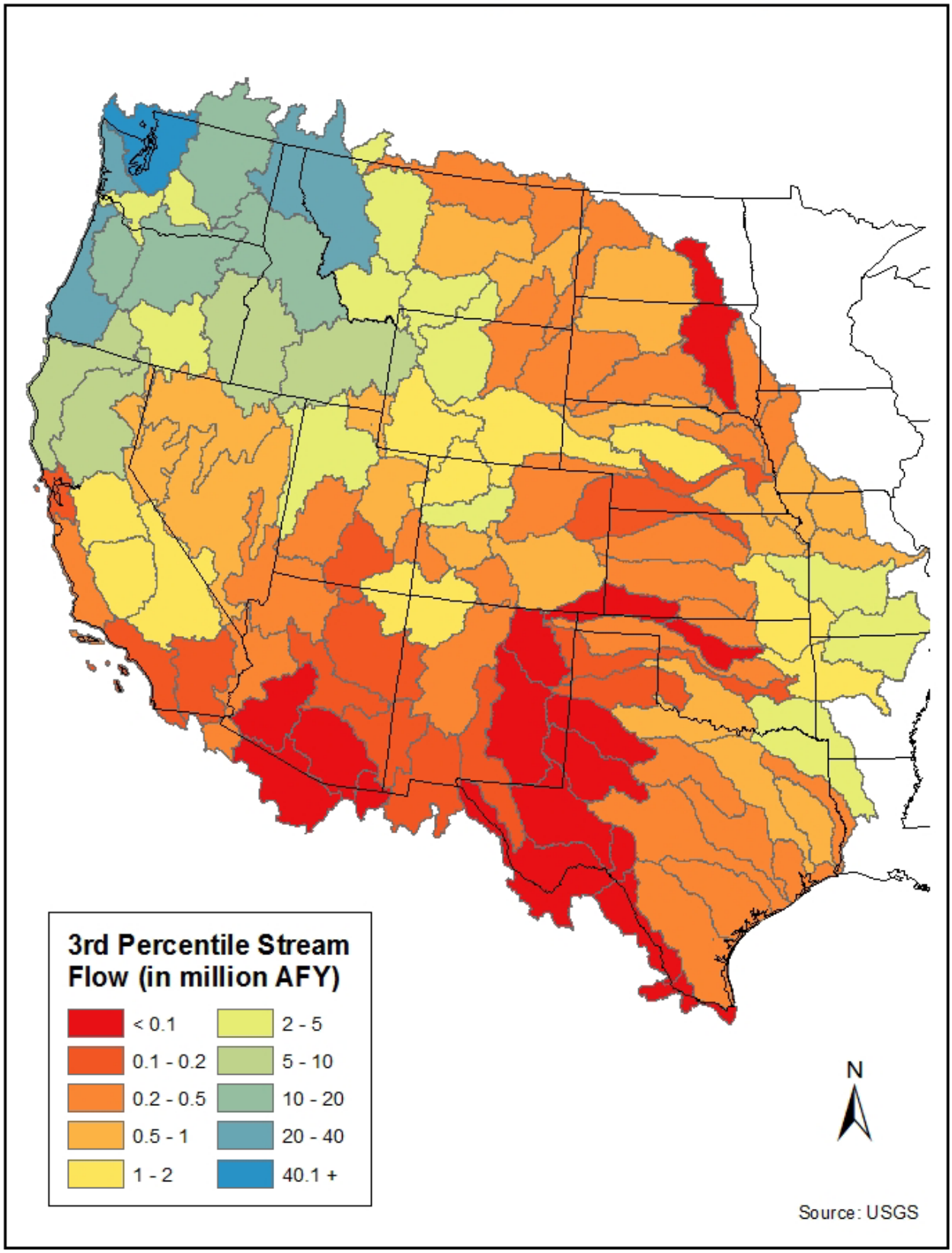

FIGURE F-3 Third Percentile Streamflow, 1950–2010

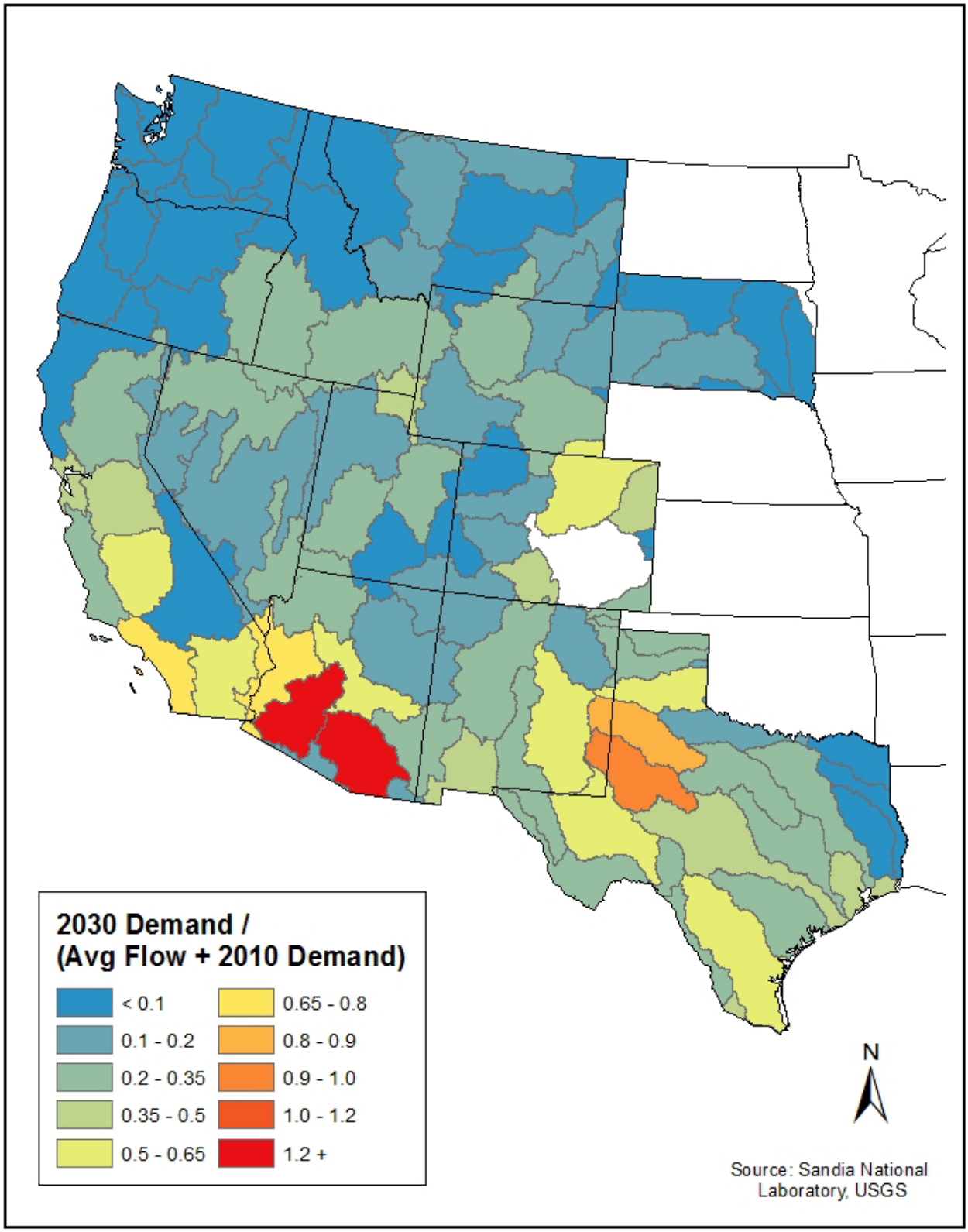

FIGURE F-4 Ratio of 2030 Demand to Average Flow

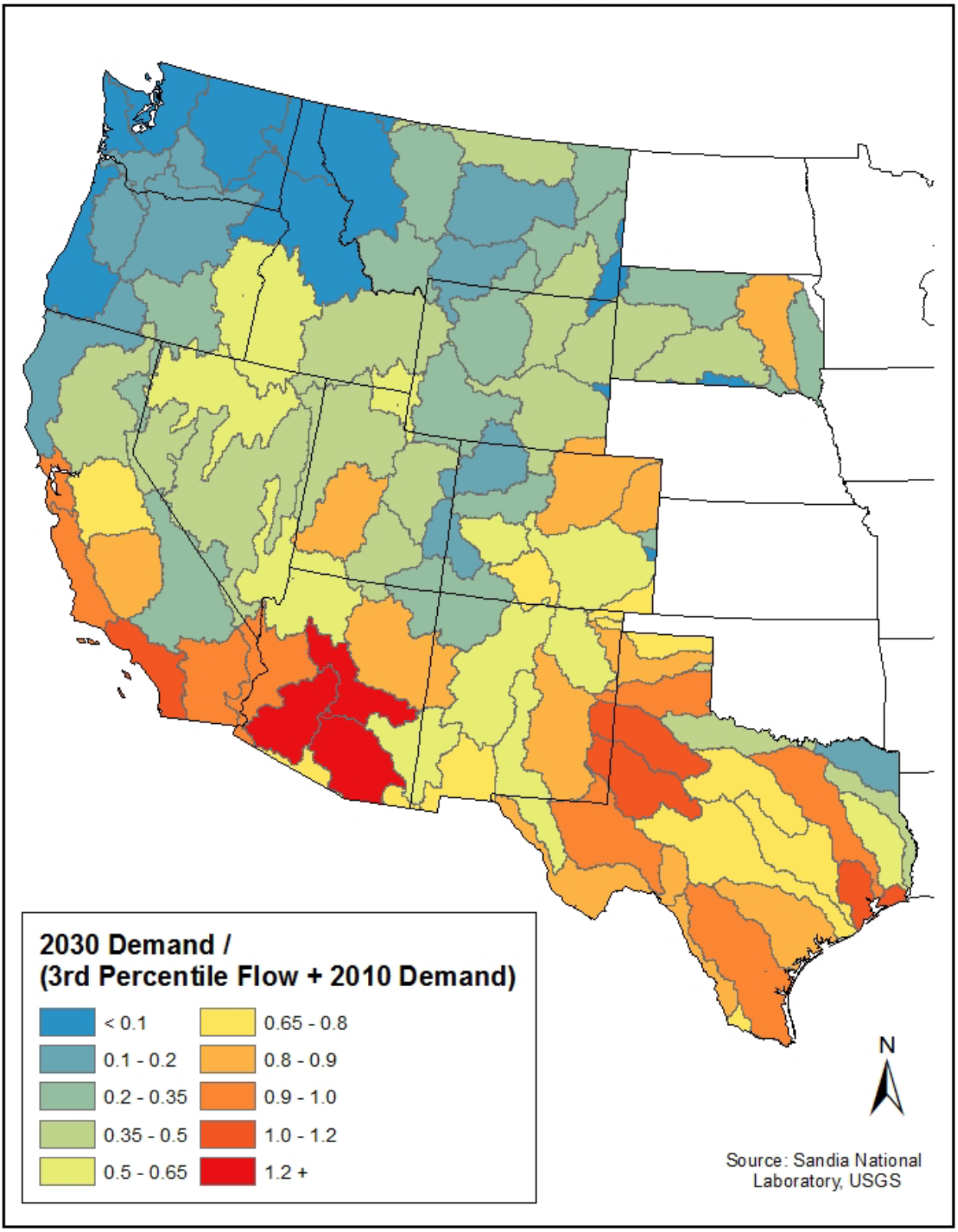

FIGURE F-5 Ratio of 2030 Demand to Third Percentile Flow

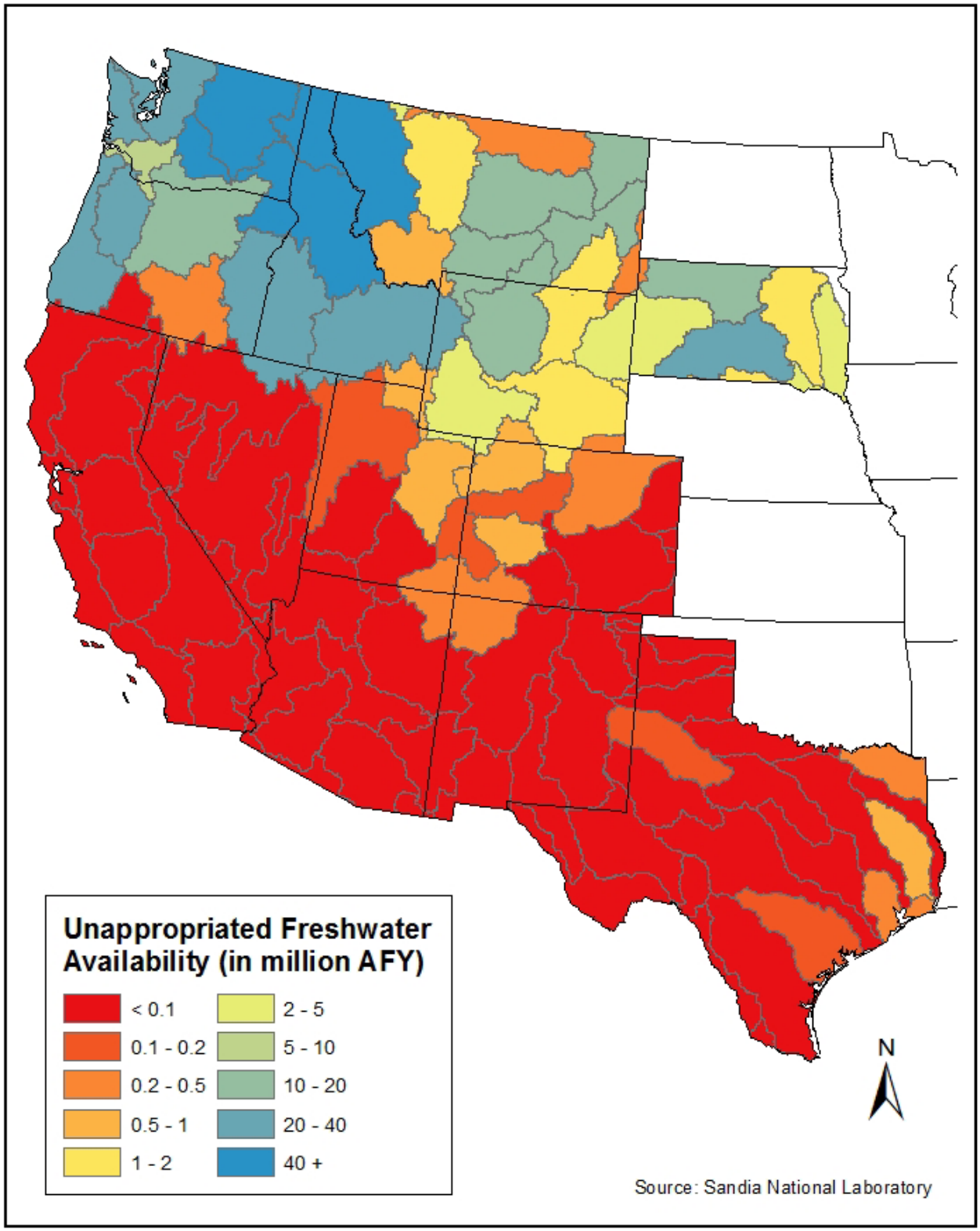

FIGURE F-6 Unappropriated Fresh Water Availability, 2030

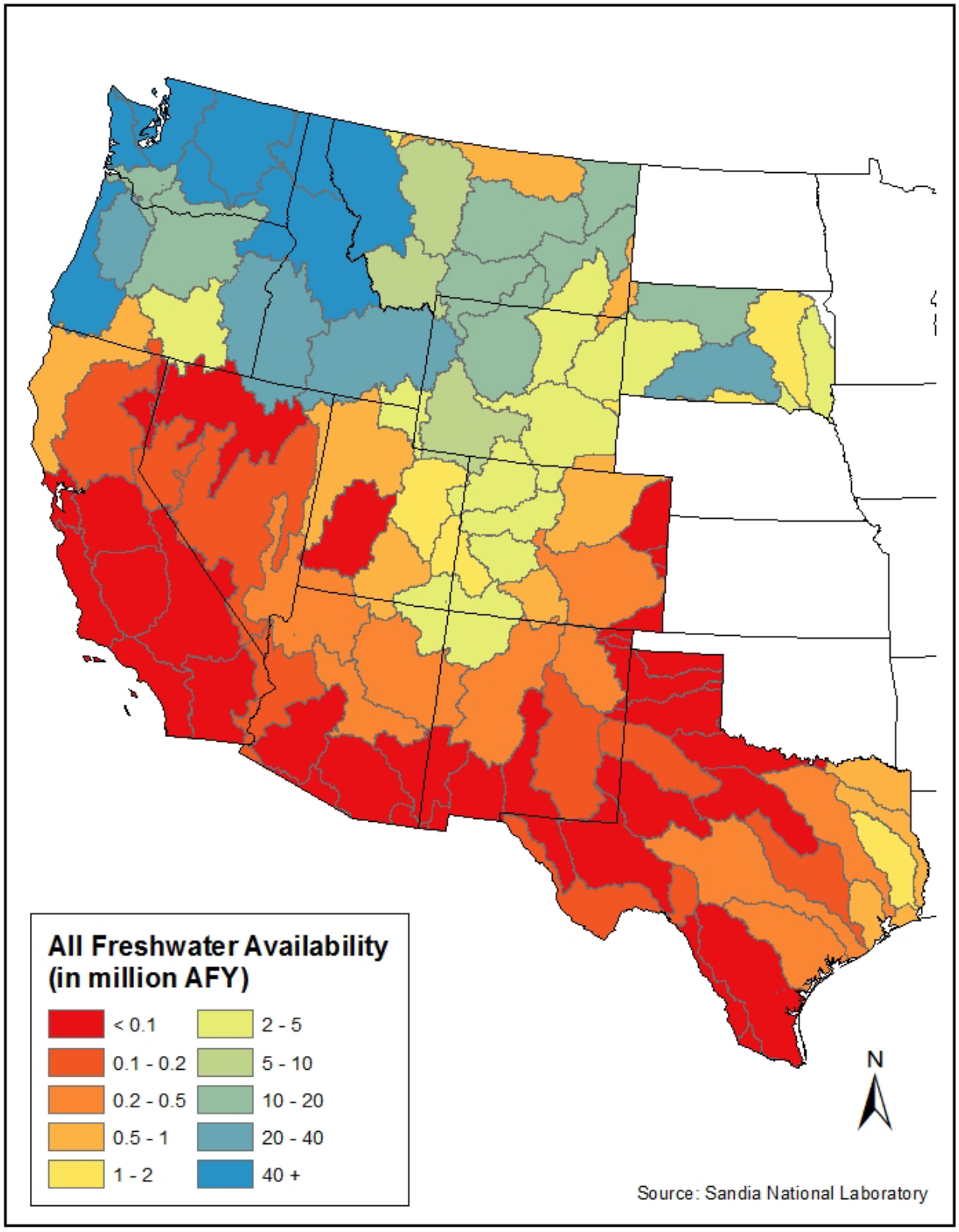

FIGURE F-7 All Fresh Water Availability, 2030

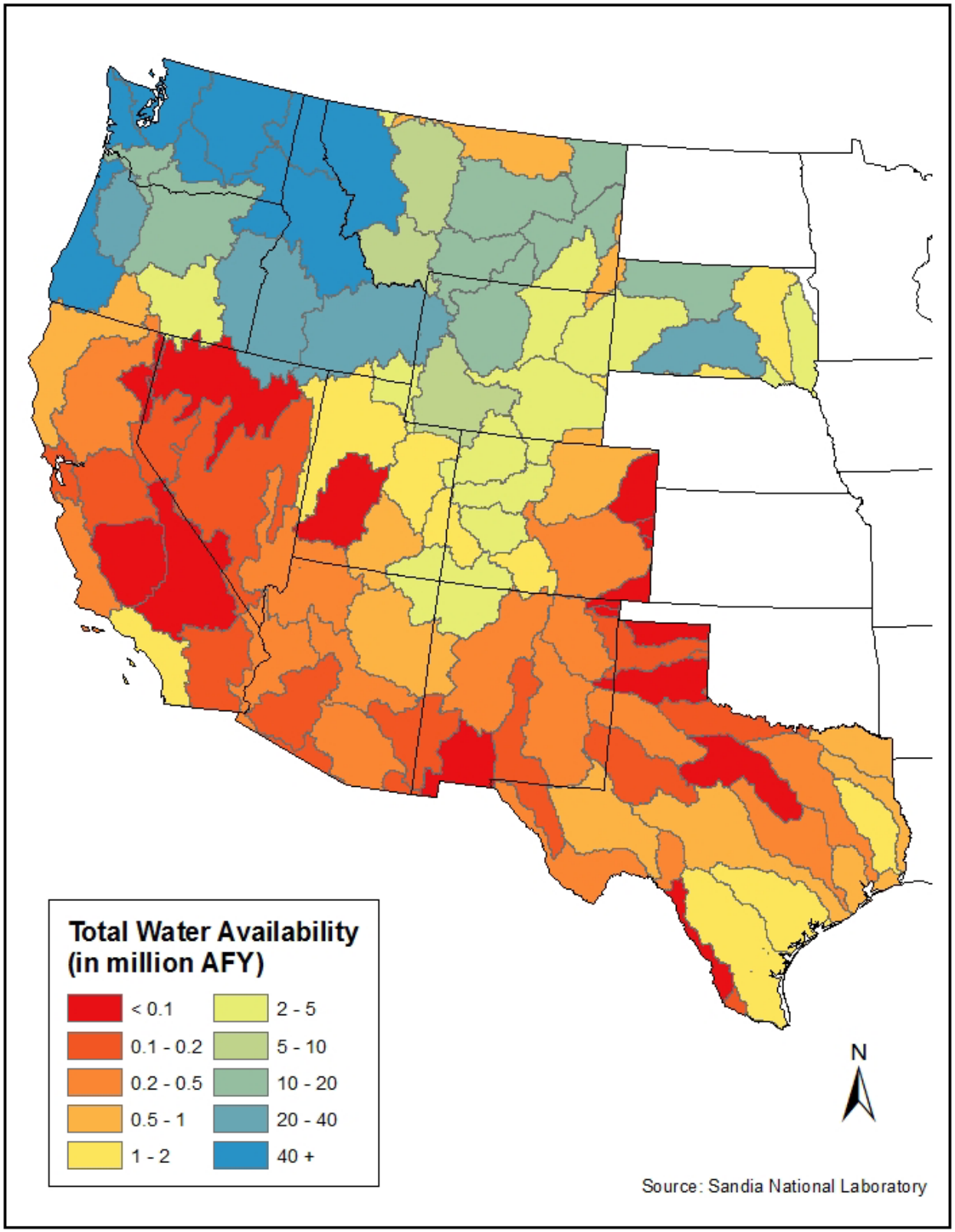

FIGURE F-8 Total Water Availability, 2030

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Argonne, IL 60439-4847

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