NREL National Renewable Energy Laboratory
A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Innovation for Our Energy Future

Updated U.S. Geothermal Supply Curve

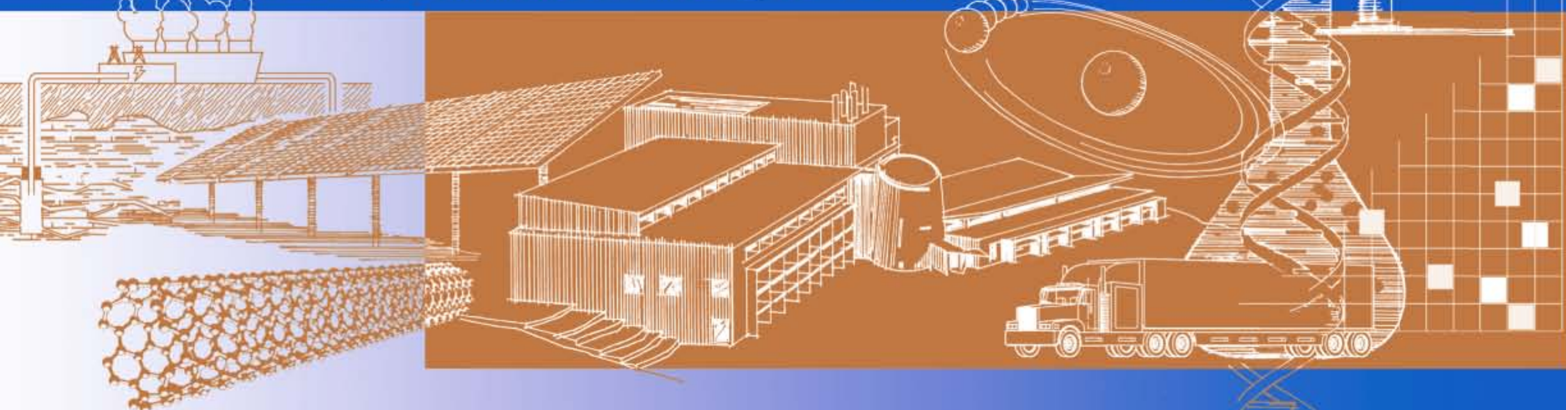
Chad Augustine and Katherine R. Young
National Renewable Energy Laboratory

Arlene Anderson
U.S. Department of Energy

Presented at Stanford Geothermal Workshop
Stanford, California
February 1, 2010

Conference Paper
NREL/ CP-6A2-47458
February 2010

NREL is operated for DOE by the Alliance for Sustainable Energy, LLC   Contract No. DE-AC36-08-GO28308



Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

UPDATED U.S. GEOTHERMAL SUPPLY CURVE

Chad Augustine

National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO, 80401-3305, United States
e-mail: Chad.Augustine@nrel.gov

Katherine R. Young

National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO, 80401-3305, United States
e-mail: Katherine.Young@nrel.gov

Arlene Anderson

U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE)
Geothermal Technologies Program (GTP)
1000 Independence Avenue, SW
Washington, DC 20585, United States
e-mail: Arlene.Anderson@ee.doe.gov

ABSTRACT

This paper documents the approach used to update the U.S. geothermal supply curve. The geothermal supply curve analysis undertaken in this study estimates the supply of electricity generation potential from geothermal resources in the United States and the levelized cost of electricity (LCOE), capital costs, and operating and maintenance costs associated with developing these geothermal resources. The supply curve data are used as input to annual reporting by the U.S. Department of Energy (DOE) under the Government Performance and Results Act of 1993, the DOE portfolio development support processes, and market penetration models in support of other DOE analyses. Supply curves were developed for four categories of geothermal resources: identified hydrothermal (6.4 GW_e), undiscovered hydrothermal (30.0 GW_e), near-hydrothermal field enhanced geothermal systems (EGS) (7.0 GW_e) and deep EGS (15,900 GW_e). Two cases were considered: a base case, which assumes modest improvements in EGS reservoir performance from current benchmarks, and a target case, which assumes significant advances in reservoir performance from the Geothermal Technologies Program (GTP or the Program) funding of EGS research, development, and demonstration projects. Project development costs for the geothermal resources in the assessment were estimated using the Geothermal Electricity Technology Evaluation Model (GETEM). Inputs for GETEM were based on probability distributions of geothermal technology costs and performance levels from experts submitted as part of the GTP's 2009 technical risk assessment. Supply curves were generated for each of the four geothermal resource categories for both the base and target cases. Capital costs by project phase for the different technologies were also calculated. For both cases, hydrothermal resources dominate the lower cost range of the combined geothermal supply curve. The supply curves indicate that the reservoir performance improvements assumed in the target case could significantly lower EGS costs and greatly increase EGS deployment over the base case. The paper discusses the results of the supply curve analysis and improvements that can be made to future supply curve representations.

INTRODUCTION AND PURPOSE

This paper documents the approach taken as part of the Department of Energy (DOE) Geothermal Technologies Program's (GTP or the Program) annual supply curve update to characterize and represent the supply of electricity generation potential from geothermal resources in the United States. The geothermal supply curve is used as the basis for input to market penetration models for an array of tasks that analyze the competitiveness of geothermal electricity generation against other forms of electricity generation and forecast the penetration of geothermal technologies into the national electricity generation market. The primary use of data from the supply curve is to provide cost input for the annual reporting under the Government Performance and Results Act of 1993 (GPRA) and for the DOE portfolio development support processes. Geothermal supply curve data are also supplied as input for numerous additional DOE analyses.

The primary purposes of this paper are to:

1. Document the approach taken in identifying geothermal resources and determining the electricity-producing potential of these resources,
2. Document the approach taken in estimating the levelized cost of electricity (LCOE), capital costs, and operating and maintenance (O&M) costs from these geothermal resources, and
3. Discuss the resulting supply curve and how improvements can be made to future supply curve representations.

For this study, the geothermal resource was broadly split between two technologies: conventional hydrothermal and enhanced geothermal systems (EGS). The hydrothermal resource consists of the naturally occurring geothermal sites conventionally used to produce electricity. Enhanced geothermal systems are artificial geothermal systems created by drilling into formations of hot rock, hydraulically stimulating the formation to open and extend fractures, intersecting the fractures with one or more drilled holes, and then circulating fluid through the fractures. Injected fluid is heated by the hot rock as it is circulated through the reservoir, brought to the surface, and then used to produce electricity in a power plant before being re-injected into the reservoir, forming a closed-loop system. To develop the supply curves for this study, the hydrothermal and EGS resources were further subdivided into four geothermal categories: identified hydrothermal, undiscovered hydrothermal, near-hydrothermal field EGS, and deep EGS.

In defining the geothermal resource, published and available resources were used whenever possible. In particular, the supply curve update benefited greatly from the geothermal resource assessment performed by the U.S. Geological Survey (USGS) in 2008 (Williams, Reed et al., 2008a). The supply curve update also drew upon methodologies and data from the Massachusetts Institute of Technology (MIT) *Future of Geothermal Energy* report to characterize U.S. EGS resources (Tester et al., 2006). The LCOE of the geothermal resources used to generate the supply curve were estimated using the Geothermal Electricity Technology Evaluation Model (GETEM), with cost input elicited from experts as part of a recent GTP geothermal technical risk assessment (Young and Augustine, 2010 (in press)). A more detailed account of the methodology and assumptions used to develop the geothermal supply curve, including additional analysis, is described in a forthcoming National Renewable Energy Laboratory (NREL) technical report (Augustine, 2010 (in press)).

GENERAL APPROACH AND ASSUMPTIONS

The same approach for generating a supply curve was used for each of the geothermal resource categories considered. The primary steps in generating a supply curve and model input were the resource characterization and the estimation of the cost of the resource. For the resource characterization, the category and scope of the geothermal resource were defined. Next, information sources were identified and gathered from the literature and other available sources. These were assembled into a database of the potential electrical generating capacity of the resource. The cost of developing each category of geothermal resource was estimated using the resource characteristics from the characterization, the technology components required to develop the resource, and any factors or assumptions included in the funding case under which the resource would be developed. The potential electrical generating capacity from the resource characterization was combined with the estimated cost of developing that capacity to generate the supply curve.

Supply Curve Cases

Two cases based on EGS reservoir technology advances were considered when developing supply curves: (1) the "base" or "no-funding" case, and (2) the "target" or "funded" case. The cases were driven by input required of all DOE energy technology programs for annual GPRA reporting, which analyzes the benefits of research, development, and demonstration (RD&D) funding for DOE programs. Technology assumptions are based on major performance goals for EGS in the Program's Multi-Year Research, Development and Demonstration (MYRD&D) plan (Geothermal Technologies Program, 2008). By 2015, the Program plans to demonstrate the ability to create an EGS reservoir capable of producing 5 MW_e. By 2020, the Program plans to validate the ability of such a reservoir to sustain 5 MW_e of power generation over a 5-year period. In the base case, expensive EGS demonstration projects were assumed too risky for private industry to undertake on a large scale, so only modest improvements are made in EGS reservoir performance from current benchmarks. In the target case, it was assumed that GTP funding of EGS RD&D projects enabled MYRD&D goals to be met, indicating that significant advances are made in EGS reservoir technology. The assumptions in each case apply to three reservoir engineering EGS enabling technology performance metrics (TPMs) identified as part of the Program's 2009 technical risk assessment (Young and Augustine, 2010 (in press)): the production well flow rate (kg/s), the thermal drawdown rate of the reservoir (%/year), and the ratio of production wells to injection wells in the reservoir. The EGS reservoir technology performance metric assumptions, which are summarized in Table 1, match those used in the risk assessment. A thermal drawdown rate of 3.0%/year corresponds to an EGS reservoir that must be re-drilled and re-stimulated once every 4-6 years, depending on its initial temperature, due to temperature declines in the produced fluid. An EGS reservoir with a thermal drawdown rate of 0.3%/year can produce fluid without significant produced-geofluid temperature decline over the 30-year lifetime of the power plant and does not require re-drilling or re-stimulation of the reservoir.

Table 1: EGS technology performance assumptions used in base and target cases.

Enabling Technology	Base Case Value	Target Case Value
Production Well Flow Rate	30 kg/s	60 kg/s
Thermal Drawdown Rate	3.0 %/year	0.3 %/year
Production/Injection Well Ratio	2:1	2:1

GETEM and @Risk

GETEM was used to estimate costs for all geothermal resources considered in this study. GETEM is a Microsoft Excel-based techno-economic systems analysis tool for evaluating and comparing geothermal project costs. It uses a bottom-up analysis to calculate the LCOE and capital costs of geothermal and hydrothermal projects based on a set of user-specified variables. The user defines the resource characteristics (e.g., hydrothermal or EGS, temperature, depth), project details (e.g., plant type and size, pump types, well productivity), and other required parameters. GETEM then calculates the individual component costs associated with each phase of the project—such as exploration, well field development, power plant construction, and O&M costs—based on user-defined cost inputs, embedded cost and system performance correlations, and cost indices to account for the year the project is developed. Total project costs are calculated assuming a user-defined fixed charge rate for project financing. GETEM's primary output is the LCOE for the project, but it also provides the total capital costs and a breakdown of capital costs and LCOE contributions from the various project phases. GETEM was developed for the GTP by Princeton Energy Resources International, LLC (PERI) (Entigh, 2006) in collaboration with researchers at the DOE national laboratories and external consultants. This study used GETEM Version 2008-A6. The current version of GETEM is available for download from the GTP Web site (Geothermal Technologies Program, 2009a). For this study, a baseline year of 2008 (the most current available in GETEM at the time) was used.

Since GETEM is a deterministic model, each set of user inputs results in a single cost output. However, input values in this study for several of the key input parameters in GETEM come from the 2009 risk assessment. This input is in the form of probability distributions of technology costs and performance levels, so that that there is a range of possible input values for some parameters rather than a single number. To accommodate these distributions, @Risk Version 5.0 software was used. @Risk is a Monte Carlo simulation add-in for Microsoft Excel available from Palisade Corporation that links directly to Excel to add risk analysis capabilities. The Monte Carlo simulation computes a probability distribution of the LCOE for a geothermal power plant project based on the probability distributions of the GETEM inputs. For each simulation in this study, 1,000 iterations were performed.

Technology Cost and Performance Data from Risk Assessment

Geothermal component technology data were elicited from experts as part of the Program's 2009 technical risk assessment. A team of geothermal experts comprised of industry experts, academic researchers, national laboratory researchers, and laboratory contractors was assembled in January 2009. Experts were divided into four geothermal technology areas: (1) exploration, (2) wells, pumps, and tools, (3) reservoir engineering, and (4) power conversion. The experts were trained on the risk assessment process, and then agreed on EGS and hydrothermal reference scenarios on which to base their component technology estimates. A summary of the risk EGS plant reference scenario is shown in Table 2. Based on their discussions, published literature, and their personal knowledge of the geothermal energy industry, the experts agreed on the current distributions (compromised of the high, low, and most likely values) for the technology performance metrics in their technology area. In all, distributions for 10 geothermal TPMs from the risk assessment were used for the supply curve study in estimating the current LCOE for geothermal resources in GETEM. These ten TPMs and the corresponding mean, 10^{th} percentile, and 90^{th} percentile values of the expert input distributions are listed in Table 3. A thorough description of the risk assessment process,

Table 2: 2009 risk assessment EGS reference scenario. Summary of reference scenario used by experts when determining technology performance metric distributions.

Parameter	Value
Geothermal Resource	EGS
Plant Type	Binary, air-cooled
Net Output	20 MW_e
Resource Temperature	225 °C
Plant Design Temperature	200 °C
Well Depth	6 km
Production Well Flow Rate	60 kg/s
Thermal Drawdown Rate	0.3%/year
Production/Injection Well Ratio	2:1

the risk geothermal plant reference scenario assumed while eliciting expert data, and the results are detailed in the Program's 2009 technical risk assessment report by Young and Augustine (2010 (in press)).

The TPM distributions were applied independently as input to GETEM in determining the LCOE for geothermal resources in current (2008) US$ for both the base and target cases, so that only the enabling technology assumptions in Table 1 differed for the two cases. Wherever possible, the distributions and assumptions used by the experts for the reference scenarios were used as guidance for inputs to parameters and values in GETEM when estimating geothermal energy costs in this analysis. However, assumptions had to be made when providing input to GETEM when (1) the characteristics of the geothermal resource for the supply curve differed from those assumed for the risk reference scenarios, (2) no relevant guidance was provided in the risk reference scenarios, or (3) the guidance in the risk reference scenarios resulted in unreasonable or unrealistic results when applied to the geothermal resource in the supply curve. For several TPMs—well costs, binary system capital costs, binary system O&M costs, and brine effectiveness—the cost or performance distribution given by the expert was specific to the power plant in the risk EGS reference scenario. To apply these distributions to the wide range of resources in the supply curve, it was assumed that the distributions given by the experts, when properly normalized, were applicable across the entire resource. For example, the well cost distribution given by the experts assumes a 6-km deep well for an EGS project. However, wells for the hydrothermal and EGS resources in the supply curve range from 0.3 km to 10 km (1,000 ft to 33,000 ft) in depth. To determine well costs in the supply curve analysis, the expert well cost distribution for the 6-km well in the risk reference scenario was normalized by the GETEM drilling cost correlation value for a medium-cost, 6-km well. The well cost input in GETEM for a given resource in the supply curve was calculated by taking the value from the normalized distribution sampled by @Risk during simulations and multiplying by the default GETEM value for the cost of a well at the depth of the geothermal resource being considered. This methodology was applied to all the scenario-specific TPM distributions mentioned above.

Since expert input was not elicited for flash plants, the GETEM-calculated values for flash plant costs and brine effectiveness were used. Sites with plant design temperatures less than 225 °C were assumed to be binary plants, while those with design temperatures of 225 °C and higher were assumed to be flash plants.

Table 3: Summary of expert-elicited geothermal technology performance metric input. Input shown is expert-consensus present-day values or distributions of TPMs for the risk reference scenario. The mean, 10th percentile, and 90th percentile values of the TPM distributions are listed.

TPM			Value		
Technology Area	Name	Units	10th %ile	Mean	90th %ile
Exploration	Non-Well Exploration Costs (EGS)	$M	0.42	1.41	2.53
	Non-Well Exploration Costs (Hydro)	$M	0.51	1.22	2.00
	Exploration Well Success Rate (EGS)	%	50.0	64.1	83.4
	Exploration Well Success Rate (Hydro)	%	20.1	34.8	50.0
Well Pumps & Tools	Well Drilling/Construction Cost	$M	15.0	22.3	30.0
	Production Pump Cost (per well)	$M	1.0	1.5	2.0
Reservoir Engineering	Stimulation Cost (per triplet)	$M	2.7	8.4	15.1
Power Conversion	Binary System Capital Cost	$/kW	2,200	2,500	2,800
	Binary System O&M Cost/Yr	¢/kWh	-	2.2	-
	Brine Effectiveness	W-h/lb_m	-	9.50	-

When the risk assessment experts met in February 2009, drilling costs were near historic highs because of the scarcity of steel and cement and increased rig rental rents caused by high crude oil and natural gas prices (which led to increased demand for oil and gas drilling). Since drilling costs are a significant factor in the overall cost of a geothermal project, changes in drilling costs have a significant impact on LCOE. GETEM uses the U.S. Bureau of Labor Statistics (BLS) Producer Price Index (PPI) to adjust drilling cost estimates to the baseline year chosen in the model. As Figure 1 shows, drilling costs have declined significantly from these recent record highs in the past year. When the supply curves in this study were generated in late summer 2009, drilling costs had decreased significantly from the values assumed during the risk assessment, but only preliminary values from the PPI were available. Based on conversations with geothermal drilling contractors, drilling costs for this study were assumed to be 30% lower than the 2008 BLS PPI index value in GETEM.

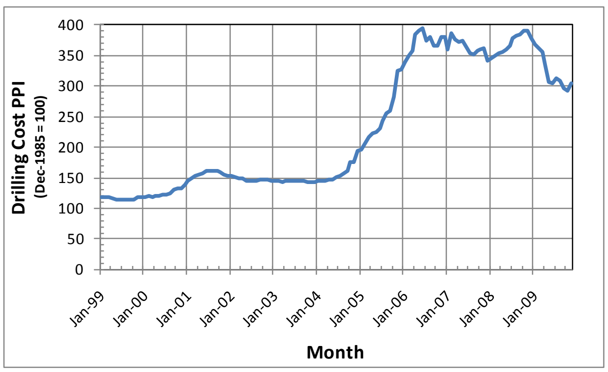


Figure 1: BLS drilling cost PPI. Index values from August 2009 onward are preliminary (Bureau of Labor Statistics, 2009).

SUPPLY CURVES

For this study, two types of geothermal resources were considered—hydrothermal and EGS. The hydrothermal resource was subdivided into two categories: identified sites and "undiscovered" resources. The EGS resource was also subdivided into two categories: the near-hydrothermal field EGS resource and the deep EGS resource. Supply curves were generated for each of the four geothermal resource categories using project costs estimated with GETEM. The supply curves are in 2008 US$.

Identified Hydrothermal Sites

Geothermal Resource

The USGS 2008 geothermal resource assessment (USGS 2008 assessment) identifies 241 moderate- and high-temperature (>90 ^{o}C) sites on private or accessible public lands in the United States (Williams, Reed et al., 2008a). The methodology used to estimate the recoverable energy from each site in the 2008 USGS assessment is similar to that used in the previous USGS Circular 790 assessment (Muffler and Guffanti, 1979), and is described in Williams, Reed et al. (2008b). To account for uncertainties in the estimate of the potential electric power generation, Monte Carlo simulations were performed. For each site, triangular distributions of the probable reservoir volume and temperature were made using estimates of the minimum, maximum, and most likely values for these parameters. The result of the Monte Carlo simulations is a distribution of probable electric power generation potential for each site. Using this methodology, the USGS 2008 assessment predicts a mean total of 9,057 MW_e of power generation potential from identified hydrothermal systems on private or accessible public lands, with a 95% probability of only 3,675 MW_e and a 5% probability of up to 16,457 MW_e being available (Williams, Reed et al., 2008a). This total mean value is significantly lower than the 23,000±3,400 MW_e potential from only 52 identified sites listed in the USGS Circular 790 assessment (Muffler and Guffanti, 1979). The primary reason for this decline is a change in the assumed recovery factor for geothermal systems. The Circular 790 assessment assumed an average recovery factor of 0.25, based on experiences at the Geysers geothermal field in California, whereas the USGS 2008 assessment used a uniform distribution ranging from 0.08 to 0.20 (0.10 to 0.25 for sediment-hosted reservoirs) based on more recent experiences from a large number of sites. Additionally, the 2008 assessment assumes reservoir volumes that are smaller for some of the large hydrothermal sites and temperatures that are lower at several sites compared with values used in Circular 790, contributing further to the apparent reduction in the overall power producing potential (Williams, 2009a).

The total mean value of 9,057 MW_e for the recoverable electric power generation potential from the USGS 2008 assessment was adopted as the starting point for the identified hydrothermal resource in this supply curve analysis. The site-specific data for the identified hydrothermal resources were obtained from the USGS (Williams, 2009b). A cut-off temperature of 110 ^{o}C was adopted because of limitations in the range of power plant operating temperatures validated in the GETEM code. This results in the removal of 106 identified hydrothermal sites representing 460 MW_e of power producing potential. The USGS 2008 assessment does not exclude currently installed generating capacity at hydrothermal sites. A review of data from the U.S. Energy Information Administration (Energy Information Administration, 2009) and the Geothermal Energy Association (Geothermal Energy Association, 2009) databases found 2,480 MW_e of installed summer hydrothermal capacity. Some sites, such as the Geysers in California, have a greater existing production capacity than the mean potential capacity, so their potential was completely removed from the supply curve analysis. When current capacity and sites with temperatures <110 ^{o}C are excluded from the USGS 2008 mean power producing potential, the subsequent remaining mean potential capacity used in this study for identified hydrothermal sites in the United States is 6,394 MW_e.

In addition to identified hydrothermal resources, the USGS 2008 assessment also estimated the power production potential from undiscovered hydrothermal resources. The undiscovered resource was estimated by using GIS-based statistical methods to analyze the correlation between spatial datasets of geological factors that are indicative of geothermal resources (e.g., heat flow and magmatic activity) to determine the probability of the existence of geothermal resources in unexplored regions (Williams and DeAngelo, 2008; Williams, Reed et al., 2008a). The undiscovered geothermal resource power generation potential from the 2008 assessment has a mean value of 30,033 MW_e, with a 95% probability of 7,917 MW_e and a 5% probability of 73,286MW_e. For this supply curve analysis, the mean value (30,033 MW_e) was used.

LCOE Estimates

The present-day LCOE in 2008 US$ for the identified hydrothermal resource was estimated using GETEM on a site-by-site basis. First, site-specific resource definitions were input into the GETEM model. The reservoir temperature and capacity were obtained from the USGS 2008 assessment (Williams, 2009b). The net power sales from the plant in GETEM were set equal to the potential capacity of the identified hydrothermal site. The plant size was capped at 100 MW_e. The reservoir depth and production well flow rates for each site were not included in the USGS data. Therefore, flow rates and depths used in a previous NREL assessment (Petty and Porro, 2007) were adopted. When data were not available, a reservoir depth of 1.524 km (5,000 ft) and a production well flow rate of 44.2 kg/s (350,000 lb/hr) were assumed.

Since the actual resource characteristics of the undiscovered hydrothermal resource, such as reservoir depth and temperature, are unknown, it was assumed that the undiscovered hydrothermal resource attributed to each state was similar to the hydrothermal resource already identified within each state. The identified sites were divided into two subgroups in each state—those with reservoir temperatures ≥150 ^{o}C and those with temperatures <150 ^{o}C—and the mean potential capacity in each subgroup was totaled. The undiscovered hydrothermal resource in each state was apportioned between the designated temperature ranges based on the percentage of identified hydrothermal resource in each subgroup. The temperature, depth, and flow rate of the undiscovered hydrothermal resource were determined by calculating the mean-capacity weighted average of each of these parameters from the identified hydrothermal sites in each sub-group. Once the undiscovered hydrothermal resource characteristics were defined in GETEM, the process and assumptions used to estimate the LCOE were nearly identical to those used for the identified hydrothermal resources, except that the power plant net power output was assumed to be 20 MW_e for each plant. Also, to account for the added expenses of locating and identifying the undiscovered sites, exploration costs were assumed to be 150% of those for identified hydrothermal resources.

The cost of power for the identified and undiscovered hydrothermal resources was calculated in GETEM using the above inputs and expert TPM inputs. For all hydrothermal sites, a 3:1 production/injection well ratio and a thermal drawdown rate of 0.3%/year were assumed. These values are consistent with those at a typical hydrothermal power plant. The resulting supply curves are shown in Figure 2. The median (50^{th}%ile), 10^{th}%ile, and 90^{th}%ile LCOE values shown illustrate the range of likely values for the hydrothermal power plants given the current state of technology based on expert input. Because the base and target case assumptions are identical for hydrothermal resources, the supply curve is identical for both cases.

<u>Near-Hydrothermal Field EGS</u>

Geothermal Resource

The near-hydrothermal field EGS resource consists of the areas around hydrothermal sites that lack sufficient permeability, in-situ fluids, or both to be economically produced as conventional hydrothermal resources. These resources require the application of EGS reservoir engineering techniques to become economic producers of electricity. Because these resources are near existing hydrothermal sites, they tend to be relatively hot and shallow, and they are likely to be the least expensive and first EGS resources to be commercially developed. The GTP is currently funding EGS demonstration projects to develop near-hydrothermal fields at the Geysers, California; Raft River, Idaho; Desert Peak, Nevada; and Brady Hot Springs, Nevada (Geothermal Technologies Program, 2009b), all of which are home to conventional hydrothermal power plants.

A formal assessment of the near-hydrothermal field EGS resource has not yet been completed. However, if the rock in and around identified hydrothermal sites are assumed to have high temperatures but to

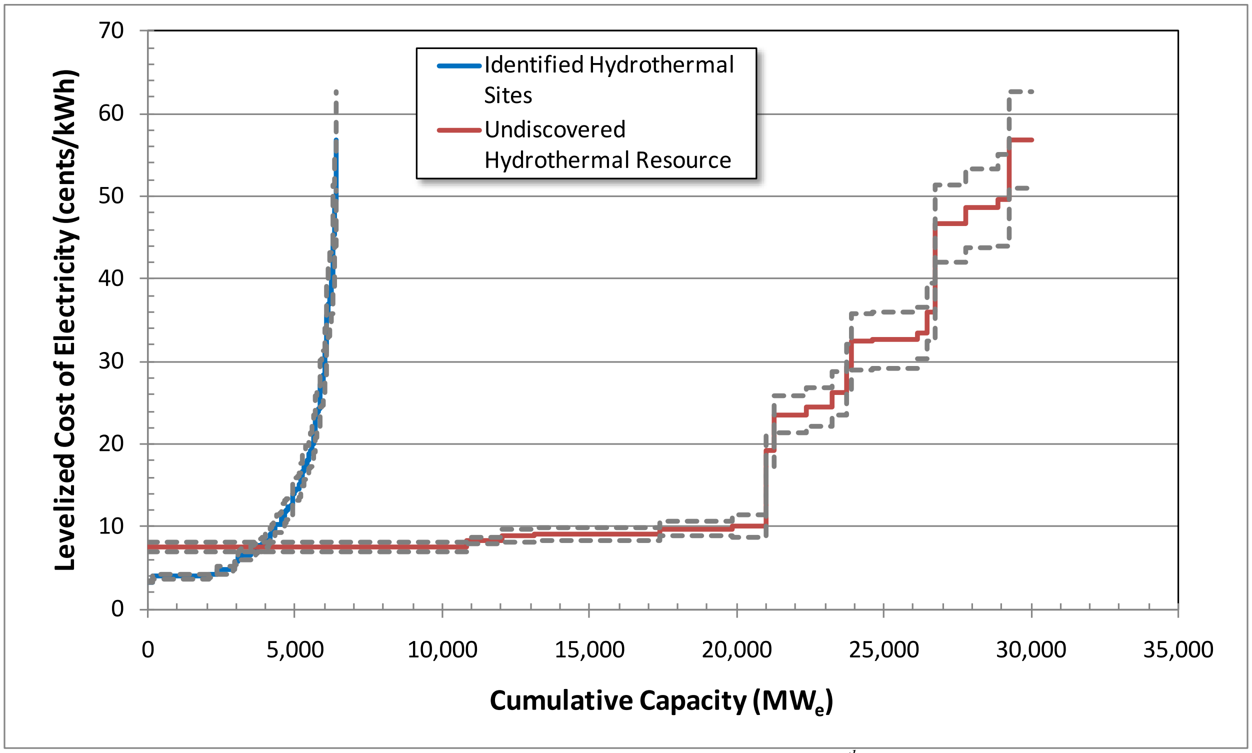


Figure 2: Supply curve for hydrothermal resource. Present-day median (50th%ile) LCOE estimates in 2008 US$ from GETEM for identified and undiscovered resources. 10th%ile and 90th%ile values for each curve shown in gray.

lack sufficient permeability or in-situ fluids to be developed commercially, a reasonable estimate of the near-hydrothermal EGS resource can be made.

For this supply curve analysis, it was assumed that the difference between the mean and high-end estimates of the electricity-generating potential capacity for each identified hydrothermal site from the USGS 2008 assessment (Williams, Reed et al., 2008a) represents a part of the reservoir that could be made to economically produce electricity using EGS reservoir stimulation techniques. When the difference between the 5% probability and mean power producing potential capacity for each identified hydrothermal site in USGS 2008 assessment sites is taken, and a reservoir cut-off temperature of 110 °C is applied, the estimate for the near-hydrothermal field EGS resource is 7,031 MW_e. The near-hydrothermal field EGS potential resource around the undiscovered hydrothermal resource was not considered for this study.

LCOE Cost Estimates

LCOE of the near-hydrothermal field EGS resource was estimated on a site-by-site basis in GETEM as it was for the identified hydrothermal resource. The reservoir temperature and depth for each near-hydrothermal filed EGS site were assumed to be the same as those for the corresponding identified hydrothermal site. The plant net power sales were set equal to the potential power capacity calculated for each site. Although the resource characteristics for each site were the same as for the hydrothermal case, the resource type in GETEM was designated EGS, so that well stimulation costs were included. The non-well exploration costs and exploration well success rate for EGS were also used, and a 2:1 production-to-injection well ratio was assumed. The production well flow rate and thermal drawdown rate of the reservoir were set to the values assumed in the base and target cases. The resulting supply curves for the base and target cases are shown in Figure 3. The 10th%ile and 90th%ile LCOE values are shown in gray to illustrate the range of likely values for the near-hydrothermal field EGS LCOE given the current state of technology based on expert input.

Deep EGS

Geothermal Resource

The deep EGS resource assessment was based on the thermal energy stored at depths 3-10 km below the Earth's surface in the continental United States. The same volume-based methodology described in a previous geothermal assessment performed by NREL (Petty and Porro, 2007) was used to determine the electricity-generating potential of the EGS resource. The supply available was based on the amount of thermal energy contained in a volume of rock. Only a fraction of this heat can be recovered and carried to

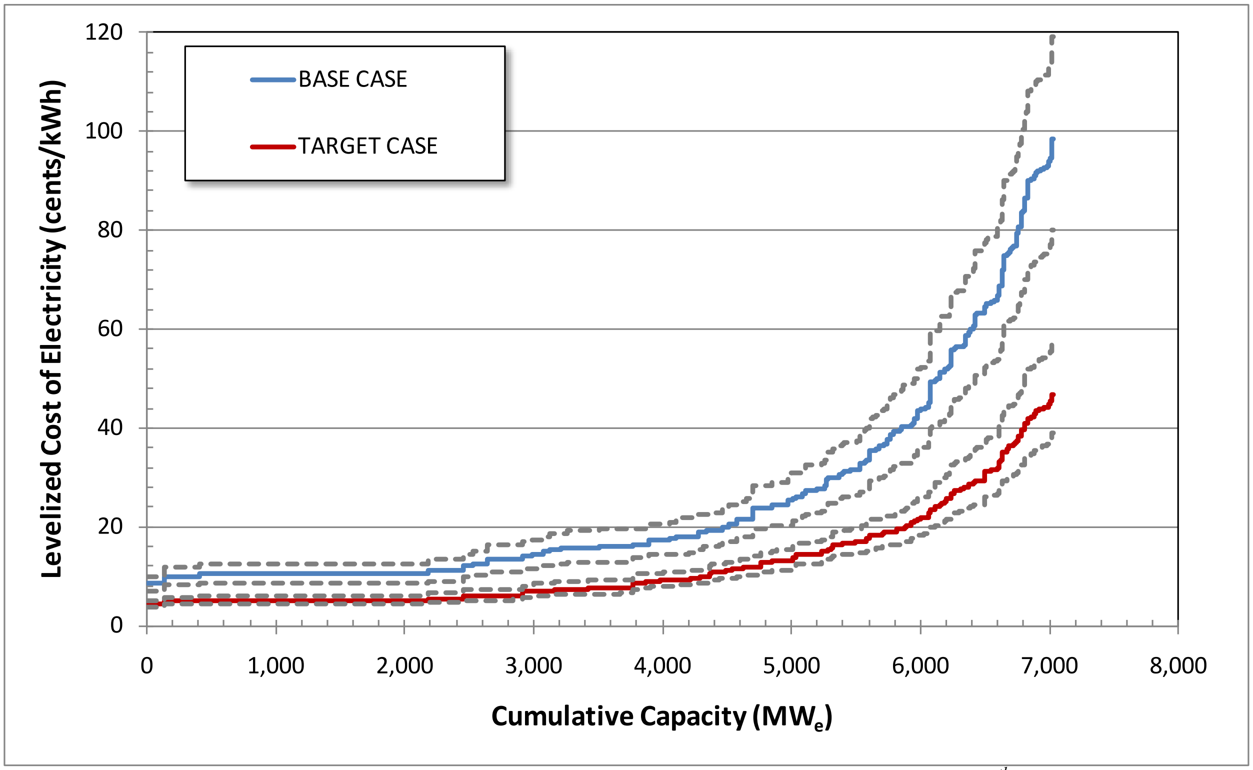


Figure 3: Supply curve for near-hydrothermal field EGS resource. Present-day median (50^{th}%ile) LCOE estimates in 2008 US$ from GETEM for base and target cases shown. 10^{th}%ile and 90^{th}%ile values for each curve shown in gray.

the surface by circulating fluid through an engineered reservoir. This fraction is defined by the recovery factor, R_g. Based on the results of a modeling study of flow in fractured systems (Sanyal and Butler, 2005), a conservative value of R_g, = 20% was assumed. This recovery factor lies at the upper end of that assumed by the USGS for hydrothermal resources in their 2008 assessment (Williams, Reed et al., 2008a; Williams, Reed et al., 2008b). The allowable temperature decline of the produced geofluid from the reservoir over its productive lifetime—and hence the allowable temperature of the rock in contact with the geofluid—is limited by the surface power plant equipment. Although the actual temperature change will vary according to proximity to fractures, the average temperature decline of rock affected by circulating fluid was assumed to be $\Delta T = 10$ °C before the produced geofluid temperature decreases to the point where the reservoir must be abandoned. The recovered thermal energy must then be converted to electric energy by a power plant at the surface. The conversion efficiency of the power plant was calculated based on an analysis of binary cycle efficiency as a function of geofluid temperature by DiPippo (2004). Finally, the potential power capacity of the plant was determined by assuming a plant lifetime of 30 years.

The deep EGS resource assessment was made using temperature vs. depth data obtained from Southern Methodist University (SMU) Geothermal Laboratory (Richards, 2009), featured in MIT's *The Future of Geothermal Energy* report (Tester et al., 2006). The data consist of the maps showing the estimated temperatures at depths of 3-10 km in 1-km intervals for the entire continental United States. Sufficient temperature and depth data to include Alaska and Hawaii were unavailable. The thermal energy in place was calculated for 1-km thick volumes at depths of 3-10 km (centered at 3.5, 4.5, 5.5, 6.5, 7.5, 8.5 and 9.5 km depths). Temperature data were binned in 50 °C increments ranging from 50-350 °C.

The areal extent of each temperature bin at each depth was determined from the SMU maps using GIS methods. Federally protected and Department of Defense (DOD) lands were excluded from the assessment. The resulting rock volume for each temperature bin at each depth interval was multiplied by the corresponding volumetric potential electric capacity. The resulting EGS electricity potential for the continental United States for each temperature-depth combination is shown in Table 4. The reservoir is assumed to extend to the bottom of each 1-km slice, so that the resource estimate for the rock centered at 3.5 km has a reservoir depth of 4 km. The resource assessment identified 15,908 GW_e of electricity producing potential, although the amount of this resource that can be economically produced is likely much smaller.

Table 4: Potential electric capacity (MW_e) of deep EGS resource for continental U.S. by temperature-depth combination.

Potential Electric Capacity (MW_e)						
		Resource Temperature (°C)				
		150-200	200-250	250-300	300-350	>350
Reservoir Depth (km)	4	91,516	117	0	0	
	5	590,763	26,526	134	0	0
	6	1,139,749	227,969	7,680	50	0
	7	1,337,049	723,692	86,057	631	0
	8	1,539,597	1,129,434	345,285	32,964	320
	9	1,881,116	1,159,750	761,653	138,204	9,922
	10	1,907,066	1,251,474	1,015,937	433,749	69,298

This assessment estimates a much larger deep EGS resource than the 518-GW_e estimate reported in the USGS 2008 assessment (Williams, Reed et al., 2008a). The USGS 2008 assessment considered only 11 states in the western United States and only depths between 3km and 6 km, whereas this resource assessment included the entire continental United States (48 states) and depths between 3 km and 10 km. Most of the roughly 16,000-GW_e deep EGS resource reported here is attributed to heat stored at depths >6 km.

LCOE Cost Estimates

The LCOE of the deep EGS resource was estimated using GETEM for each temperature-depth combination listed in Table 4. First, the resource was defined in GETEM for each combination. The reservoir and well depths both were assumed to extend to the full depth of each 1-km slice, so that the 3-4 km region is assumed to have reservoir and well depths of 4 km. Since the temperatures in each interval tend to be skewed toward lower values, the reservoir temperature was assumed to be 12.5 °C (1/4 of interval) above the lower end of interval (i.e., 150-200 °C temperature interval was assumed to have a reservoir temperature of 162.5 °C). The production well flow rate and thermal drawdown rate of the reservoir were set to the values assumed in the base and target funding cases. Once an LCOE was estimated for each temperature/depth interval combination, the results were coupled to the available capacity in Table 4 to generate the deep EGS resource supply curve. The resulting supply curves for the base and target cases are shown using a semi-logarithmic scale in Figure 4. The graph is truncated to the first 1,000 GW_e of power capacity. The 10th%ile and 90th%ile LCOE values are shown in gray to illustrate the range of likely values for the deep EGS power plants in the base and target funding cases given the current state of technology based on expert input.

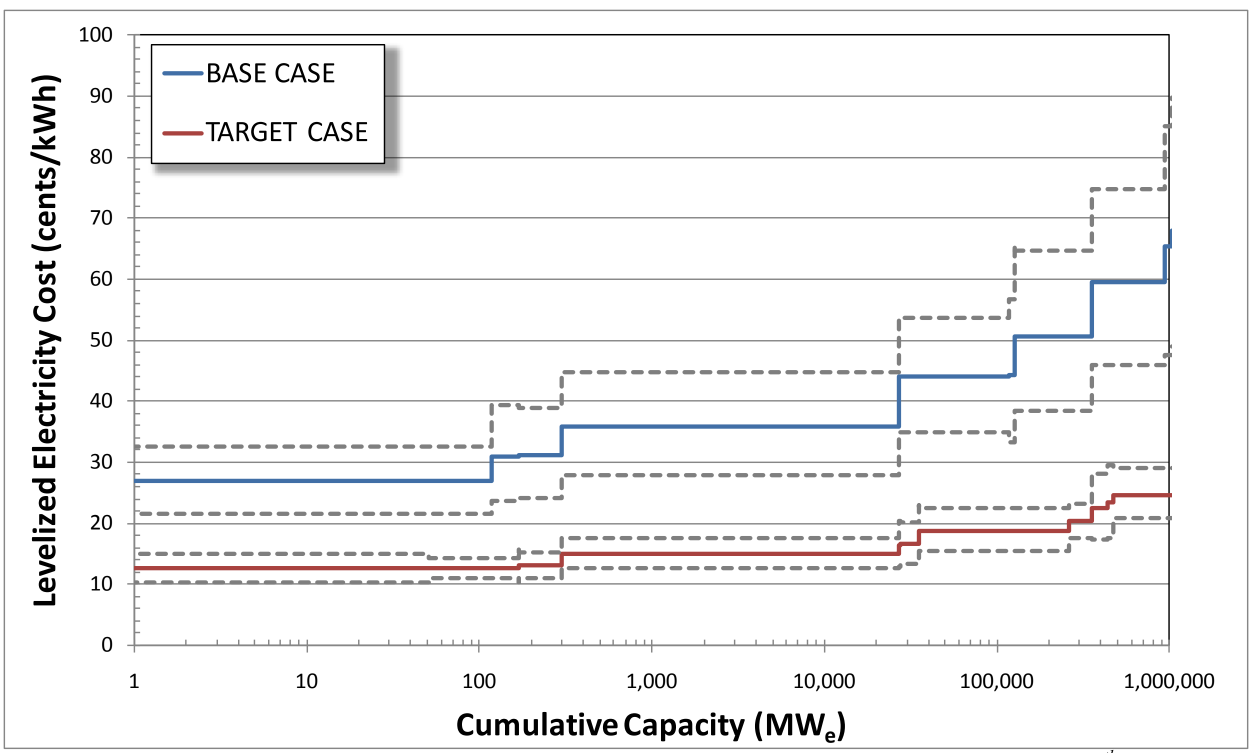


Figure 4: Supply curve for deep EGS resource using semi-logarithmic scale. Present-day median (50th%ile) LCOE estimates in 2008 US$ from GETEM shown for base and target cases. 10th%ile and 90th%ile values for each curve shown in gray. Supply curve truncated to the first 1,000 GW_e of potential power capacity.

Co-Produced and Geopressured Resources

This supply curve analysis considered only conventional hydrothermal and EGS technologies and did not address all geothermal technologies that can be used to produce electricity. In particular, electricity generation potential from fluids co-produced during oil and gas production, from abandoned oil and gas wells, and from "geopressured" resources was not considered. The co-produced fluid resource estimate in the last NREL assessment (Petty and Porro, 2007) was based on the volume of water produced during oil and gas production (Curtice and Dalrymple, 2004) and electricity generating potentials from the MIT report based on a range of assumed co-produced fluid temperatures (Tester et al., 2006, pp. 2-29, 2-48), not actual temperature data. Also, (Petty and Porro, 2007) triple-counted the size of resource by treating the different temperature assumptions in the MIT report as individual resources. The authors of this analysis felt that there was insufficient data to make reasonable estimates of the co-produced and geopressured geothermal resources. An effort to perform an accurate assessment of the co-produced fluid geothermal resource is planned and will be included in future supply curve updates.

RESULTS AND DISCUSSION

Summary of Results

A summary of the results of the geothermal resource characterization included in the supply curve is given in Table 5. Although estimates of the geothermal resource were made using the best available data, future estimates will likely differ as new hydrothermal sites are discovered and better data and methodologies become available for estimating the capacity of the geothermal resources. Future supply curve analyses will also be aided by the new National Geothermal Data System (NGDS), which was funded under the American Recovery and Reinvestment Act of 2009. The goal of the NGDS project is to assess and classify all geothermal resources and facilitate access to geothermal data sets for developers to lower the risk associated with the development of geothermal projects.

The supply curves for the separate geothermal technologies were combined to produce a single aggregated supply curve for all geothermal technologies for the base and target cases and are shown in Figure 5. Portions of the supply curves overlap because assumptions for identified and undiscovered hydrothermal are the same for both cases. The supply curves have been truncated to show only the first 50 GW_e of potential capacity to

Table 5: Summary of geothermal resource characterization used in the supply curve analysis.

Resource		Resource Potential Capacity	
		Capacity (GW_e)	Source(s) and Description
Hydrothermal	Identified Hydrothermal Sites	6.39	USGS 2008 Geothermal Resource Assessment[1] - Identified hydrothermal sites - Sites ≥110 °C included - Currently installed capacity excluded
	Undiscovered Hydrothermal	30.03	USGS 2008 Geothermal Resource Assessment[1]
Enhanced Geothermal Systems (EGS)	Near-Hydrothermal Field EGS	7.03	Assumptions based on USGS 2008 assessment[1] - Regions near identified hydrothermal sites - Sites ≥110 °C included - Difference between mean and 95th %ile hydrothermal resource estimate
	Deep EGS	15,908	NREL 2006 Assessment[2], MIT Report[3], SMU Data[4] - Based on volume method of thermal energy in rock 3-10 km depth and ≥150 °C - Does not consider economic or technical feasibility

[1] (Williams, Reed et al., 2008a)
[2] (Petty and Porro, 2007)
[3] (Tester et al., 2006)
[4] (Richards, 2009)

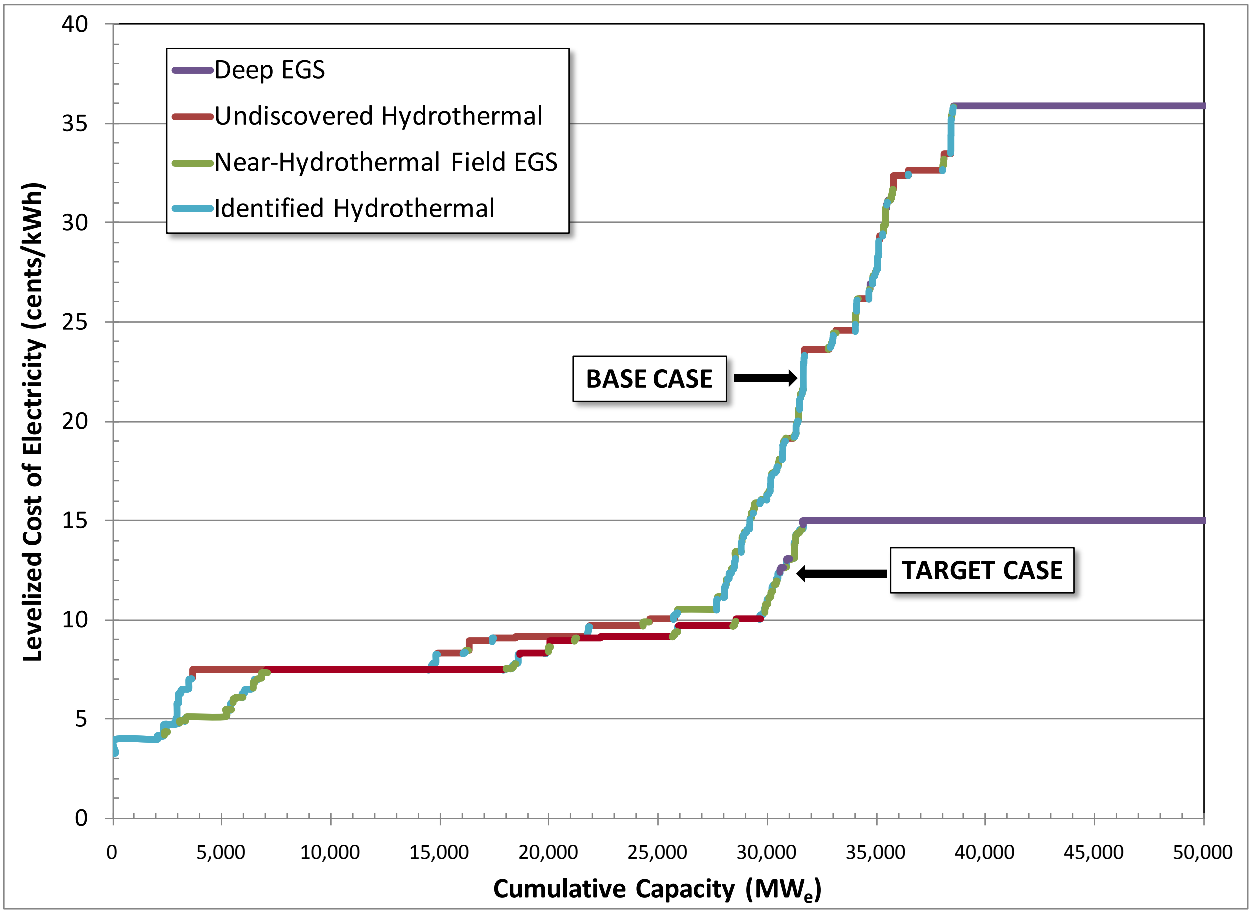


Figure 5: Aggregated supply curves of the four geothermal technologies analyzed for base and target cases.

emphasize the lowest cost resources that are likely to be developed first. The aggregated supply curve shows the likely order in which resources would be developed based on the LCOE estimated by GETEM. Market penetration models consider a wide range of factors, such as capital costs, O&M costs, technology readiness time frames, future cost multipliers, and model-specific assumptions about financing and project development times, to calculate and compete the costs of developing resources, so the models differ slightly from each other and from Figure 5 in the order they build out the resources. However, the calculated LCOEs of a resource give a good approximate measure of the most economical resources to build.

Compared to the base case, the target case sees an increase in the number of near-hydrothermal field EGS projects included in the most cost-effective 50 GW_e of potential capacity. The target case also contains a large amount of deep EGS at a significantly lower LCOE than in the base case. The large amount of deep EGS capacity shown by the purple line in Figure 5 that extends beyond the scale of the graph represents the 5km-200°C depth-temperature combination deep EGS resource. It consists of over 25,000 MW_e of potential capacity. The target case assumes that EGS reservoir technology has advanced to the point where reservoirs can be reliably engineered with production well flow rates of 60 kg/s and thermal drawdown rates of 0.3%/year (versus 30 kg/s and 3.0%/year respectively for the base case). The large decrease in costs in the target case for the EGS projects is due to these advances in EGS reservoir performance that require fewer wells to be drilled for the power plant and no additional costs incurred for drilling and stimulating new reservoirs over the lifetime of the power plant.

All geothermal technologies in this supply curve analysis, especially EGS, saw higher costs compared to those in the previous NREL supply curve analyses (Petty and Porro, 2007), primarily because of increases in drilling costs. (Petty and Porro, 2007) assumed 2004 drilling costs, which were much lower than current drilling costs (see Figure 1). Even though drilling costs in this study were assumed to be 30% less than the 2008 drilling cost index value in GETEM, drilling costs were still 64% higher than the index value used in 2004. This added significantly to the capital costs of geothermal projects. The capital costs estimated by GETEM for each of the geothermal technologies were broken down into four cost groups:

1. Exploration/confirmation costs
   - Non-well exploration costs
   - Exploration well costs
   - Confirmation well costs (two confirmation wells, which are later used as production wells, are required to prove the resource)
2. Drilling costs: Costs of drilling remaining injection and production wells
3. Other well-field costs (non-drilling)
   - Injection and production pumps
   - Reservoir stimulation costs (for EGS sites)
4. Power plant costs: Cost of equipment and construction

The breakdown of capital costs follows the phases of development for a geothermal project. The exploration and confirmation phase carries a much higher risk of failure than the later phases (Deloitte, 2008). Acquiring capital for this early phase before the resource is confirmed is more difficult and carries a higher cost of capital, usually as equity financing. Once exploration and confirmation is complete, the success rate of the project increases and capital can be acquired at lower interest rates, usually as debt financing.

Capital costs were calculated and are presented for all the geothermal technologies and cases in the forthcoming NREL full technical report (Augustine, 2010 (in press)). A breakdown of the capital costs for the target case of the deep EGS resource temperature/depth combinations in Table 4 is shown in Figure 6. Even for deep EGS resources with relatively low capital costs, most of the capital costs are associated with drilling exploration, confirmation, and injection and production wells due to the depth of the resource. The stimulation and power plant costs are relatively small in comparison except for the highest quality resources. The target case has significantly lower drilling costs than the base case because a production well flow rate of 60 kg/s (versus 30 kg/s for the base case) is assumed; thus, fewer wells need to be drilled for a given power plant output. Decreasing drilling costs will be an important step in developing the deep EGS resource at a large scale in the future.

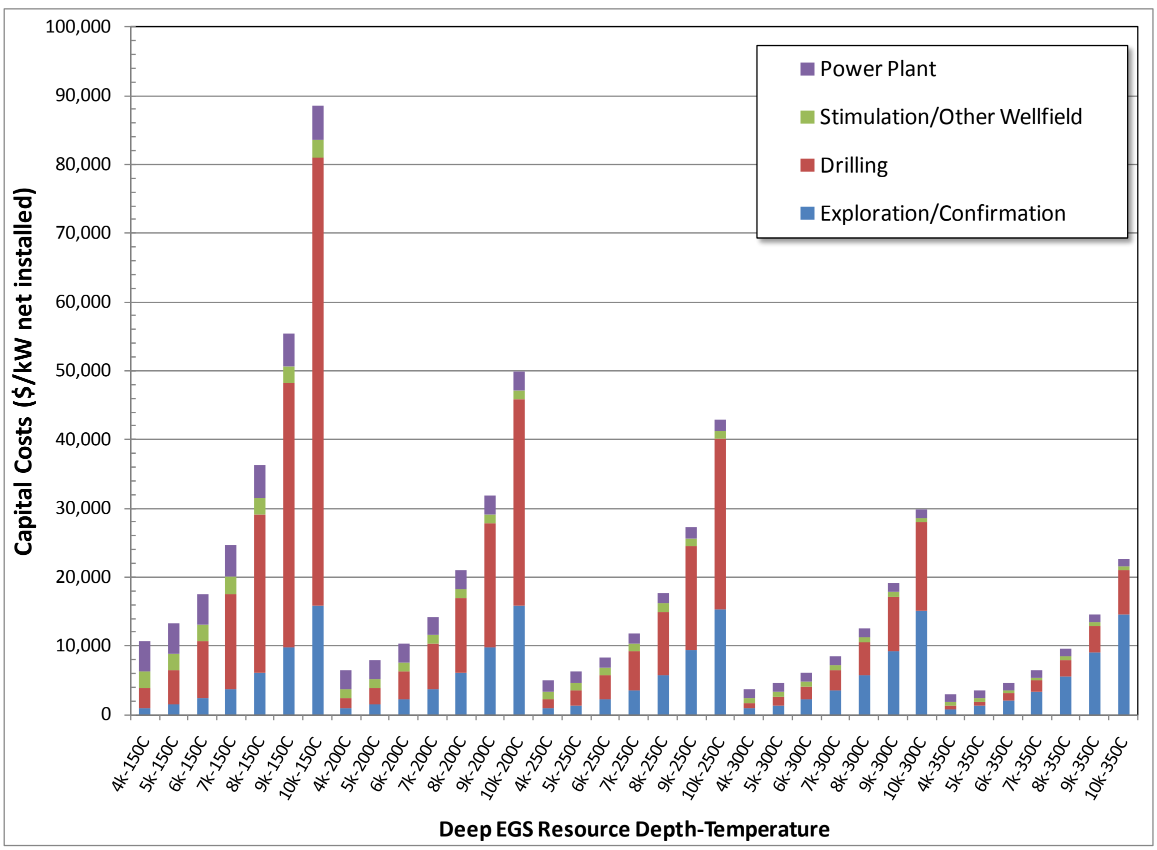


Figure 6: Deep EGS resource capital costs for target case. The breakdown of the capital costs by project phase is given for each temperature-depth combination listed in Table 4. The lower bound of the reservoir temperature in each depth interval was used to identify the resource so that "4k-150C" represents the deep EGS resource with a reservoir depth of 4 km and temperature of 150-200 °C.

Optimum Deep EGS Resource Depth

The supply curve analysis assumes that deep EGS resources can be developed at all depths at a given location. If a deep EGS resource is developed at one depth in a given location, the supply curve does not remove the resource at the remaining depths in that location from potential development; it assumes that if a reservoir is artificially created at 4-km depth, another reservoir could still be developed at the same location at 5 km, 6 km, 7 km, and so on. Given the current state of the technology, this type of development is unlikely. The most-economical deep EGS resource based on the temperature vs. depth profile at a location is most likely to be developed, and its presence would preclude the development of the remaining resource in that location for the lifetime (assumed to be 30 years) of the power plant.

The optimal thickness of the developed depth at a given location may vary. As a first look, the optimum reservoir depth, assuming a 1-km thick reservoir, by location in the continental United States was determined based on the LCOE values estimated by GETEM for the target case using GIS mapping methods. For each point on the map, the LCOE for the deep-EGS resources at depths from 3-10 km (in 1-km increments) were compared, and the 1-km thick slice with the minimum LCOE was selected. The results were used to create a map to illustrate the location of the most cost-effective regions for developing the deep EGS resource based on the analysis in this study. Regions were grouped by favorability, with regions having the lowest LCOE being the most favorable and those having the highest being the least favorable. By grouping the data, the transition between resources is smoothed and the classification generalized, so that the results should apply even with variations in some of the underlying costs or assumptions used in this study. The location of the identified hydrothermal sites (and hence the assumed near-hydrothermal field EGS resource) was also included. The resulting map, shown in Figure 7, neatly summarizes the majority of the geothermal resources of the United States. The LCOE was not assessed in regions where the temperature was not above 150 ^{o}C at the maximum considered depth of 10 km; these locations are indicated in green.

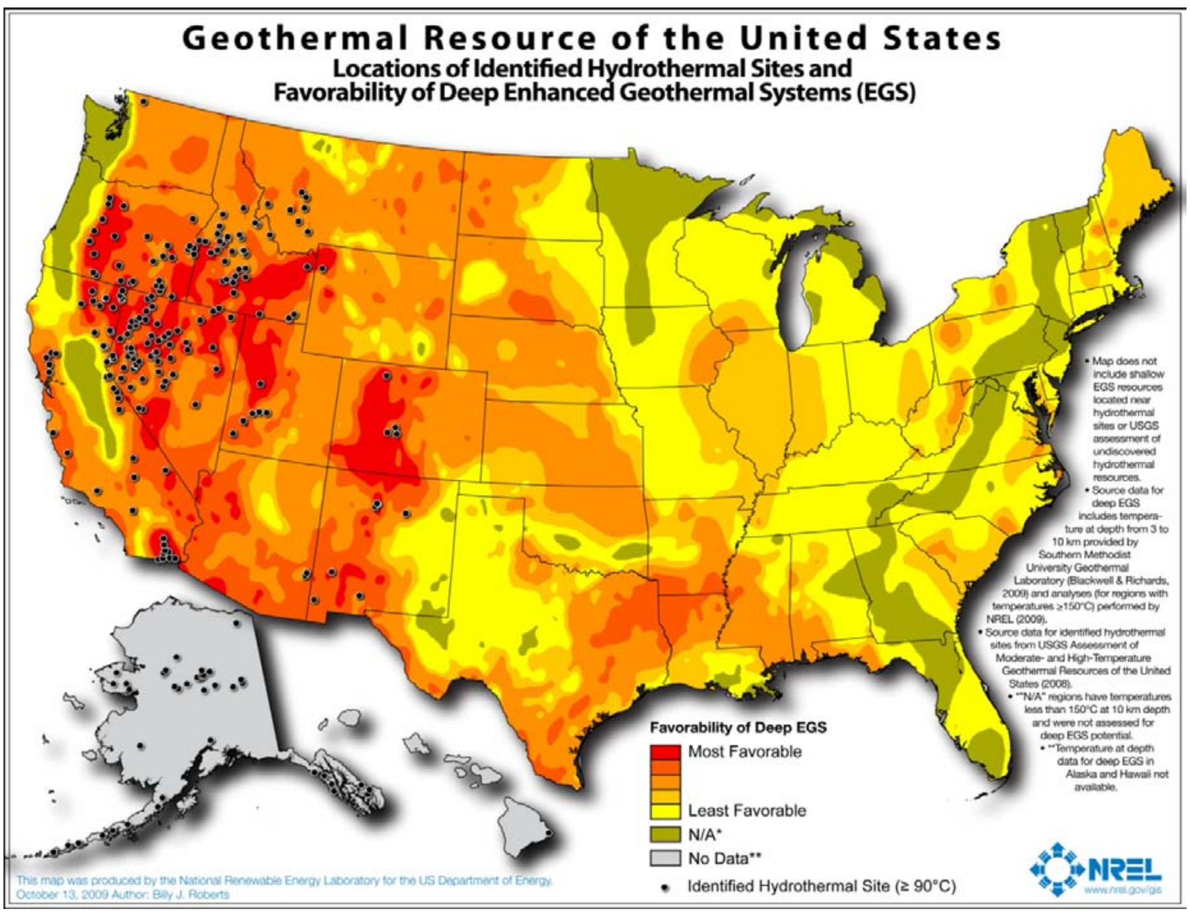


Figure 7: Geothermal resource of the United States. Figure shows the location of identified hydrothermal sites, the co-located near-hydrothermal field EGS resource, and the favorability of the deep EGS resource by location. The undiscovered hydrothermal resource and other geothermal resources, such as co-produced fluids, are not represented.

This geothermal supply curve analysis found that the most favorable cost resources have reservoir temperatures that are almost entirely between 150^o C and 250 ^{o}C. Although higher temperature reservoirs exist, they are at greater depths, which means the drilling costs associated with developing them result in a higher estimated LCOE. Another interesting result was that almost all optimum reservoir depths are 5 km or deeper. The deep EGS supply curve analysis determined that it was more economic to continue drilling beyond 4 km to encounter higher temperature reservoirs.

The results of this analysis are not definitive and come with significant caveats. First, the results are unique for the EGS reservoir technology performance levels assumed in the base and target cases. Achieving higher production well flow rates or higher production-to-injection well ratios could lower drilling costs and change the landscape. Reliable expert data on these reservoir TPMs should be obtained and used in future supply curves. Second, the underlying temperature-depth data used in the deep EGS assessment are applied over large areas, are not accurate to fine scale, and are based on sparse data in some regions. Localized hot spots are likely not captured by the data used in the assessment where high reservoir temperatures exist closer to the surface. Third, a single drilling cost curve was used for the entire continental United States. Regions of easy or difficult drilling will affect drilling costs and change the contour of the maps. A change in drilling costs that is due to natural market forces could also affect the results of the optimum LCOE analysis. Given these caveats, this analysis suggests that future deep EGS RD&D should focus on drilling wells 5 km and deeper and power plants operating in the 150-250 ^{o}C range.

CONCLUSIONS AND RECOMMENDATIONS

This geothermal supply curve study (Augustine, 2010 (in press)) updated the geothermal supply curve of the United States for use as input into market penetration models and GPRA benefits analysis. The study established an approach and methodology for estimating geothermal resource potential that can be easily updated when new resource and cost data become available. The resource characterization made use of published and available data on geothermal resources, in particular the results of the USGS 2008 geothermal resource assessment. When sufficient information was not available, methodologies and assumptions were established for estimating geothermal resource potential. The results of the potential capacity estimates for the four geothermal resource categories considered were:

- Identified hydrothermal resource (current capacity excluded): 6.39 GW_e
- Undiscovered hydrothermal resource: 30.03 GW_e
- Near-hydrothermal field EGS resource: 7.03 GW_e
- Deep-EGS resource: 15,908 GW_e

Supply curves based on the median, 10th%ile, and 90th%ile estimates of the LCOE were generated for each of the resource categories using GETEM and input from the 2009 geothermal risk assessment. The individual supply curves were combined to create aggregated supply curves for the base and target cases. The aggregated supply curves focused on the most cost-effective 50 GW_e of geothermal resource. For the base case, identified and undiscovered hydrothermal resources dominate the lower part of the curve, with some EGS present at higher LCOE values. For the target case, hydrothermal sites still dominate the lower part of the curve, but a significant amount of near-hydrothermal field EGS resource is visible. The cost level at which a large amount of deep EGS resource is found in the supply curve is significantly lower for the target case than in the base case, indicating that meeting GTP technology goals could have a significant impact on deep EGS deployment and that research should focus on EGS reservoir engineering improvements. The results of the target case are heavily dependent on the EGS reservoir technology performance metric assumptions used: 60 kg/s production well flow rate, 0.3%/year thermal drawdown rate, and 2:1 production/injection well ratio. GIS tools were used to identify and map the favorability of the deep EGS resource by location.

Capital costs by project phase for the different technologies were also calculated. For the deep EGS resource, drilling costs are the dominant component of the total capital costs. LCOE and capital costs were generally higher for all geothermal resources in this assessment than in the last NREL study (Petty and Porro, 2007) mainly because of a significant increase in drilling costs over the past several years. The previous study assumed 2004 drilling costs, while this study assumed that drilling costs were 30% lower than the 2008 drilling cost PPI value in GETEM based on conservations with geothermal drilling companies. Even at this lower value, the index value used to adjust drilling costs in GETEM was 64% higher than its 2004 value. The results of the analysis are heavily influenced by the assumptions made for the base and target case, the current drilling cost trend, and the accuracy of the resource assessments.

There is ample room for improvement in quantifying the geothermal resource as the quantity and quality of geothermal resource data continue to increase. Both the undiscovered hydrothermal and near-hydrothermal field EGS resource assessments rely heavily on assumptions. The deep EGS resource is based on data that are sparse in many parts of the country. Additional efforts are needed to better characterize these resources. A co-produced fluid resource assessment is also needed. Much of these data will be gathered as part of the National Geothermal Data System, resource assessments, and a classification project recently funded by the GTP and can be used in future supply curves. General recommendations for improvements to the supply curve cost estimates are to improve expert input during the risk assessment process, especially for EGS reservoir TPMs and the application of the expert input to the full range of geothermal resources, the inclusion of resource uncertainty measurements in the supply curve, and the development of drilling cost models that take into account local lithology and well diameter.

REFERENCES

Augustine, C. (2010 (in press)), "Updated U.S. Geothermal Supply Curve for Market Penetration Model Input." NREL/TP-6A2-47459. Golden, CO. National Renewable Energy Laboratory.

Bureau of Labor Statistics. (2009), "Producer Price Index Industry Data: Drilling Oil, Gas, Dry, or Service Wells: PCU21311121311101." http://www.bls.gov/data/. Accessed December 28, 2009.

Curtice, R. J. and Dalrymple, E. D. (2004), "Just the Cost of Doing Business?" *World Oil*, **225**(10), 77-78.

Deloitte. (2008), "Geothermal Risk Mitigation Strategies Report." http://www1.eere.energy.gov/geothermal/pdfs/geothermal_risk_mitigation.pdf.

DiPippo, R. (2004), "Second Law Assessment of Binary Plants for Power Generation from Low-Temperature Geothermal Fluids." *Geothermics*, **33**, 565-586.

Energy Information Administration. (2009), "Form EIA-860 Database Annual Electric Generator Report." U.S. Department of Energy, http://www.eia.doe.gov/cneaf/electricity/page/eia860.html. Accessed December 28, 2009.

Entigh, D. J. (2006), "Introduction to the Geothermal Electricity Technology Evaluation Model (GETEM)." Rockville, MD. Princeton Energy Resources International.

Geothermal Energy Association. (2009), "Geothermal Plants." http://www.geo-energy.org/information/plants.asp. Accessed June 1, 2009.

Geothermal Technologies Program. (2008), "Multi-Year Research, Development and Demonstration Plan: 2009-2015 with Program Activities to 2025." Washington, DC. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, http://www1.eere.energy.gov/geothermal/pdfs/gtp_myrdd_2009-complete.pdf.

Geothermal Technologies Program. (2009a), "Geothermal Electricity Technology Evaluation Model (GETEM), Version 2008-A6." U.S. Department of Energy Geothermal Technologies Program, http://www1.eere.energy.gov/geothermal/getem.html. Accessed May, 2009.

Geothermal Technologies Program. (2009b), "Geothermal Technologies Program Projects." U.S. Department of Energy Geothermal Technologies Program, http://apps1.eere.energy.gov/geothermal/projects/. Accessed November 4, 2009.

Muffler, L. J. and Guffanti, M. (1979), "Assessment of Geothermal Resources of the United States - 1978." Circular 790. Washington, D.C. U.S. Dept. of Interior, Geological Survey, http://www.geo-energy.org/aboutGE/potentialUse.asp.

Petty, S. and Porro, G. (2007), "Updated U.S. Geothermal Supply Characterization." Proceedings, Thirty-Second Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA.

Richards, M. (SMU Geothermal Laboratory) (2009), E-mail message to C. Augustine, May 29, 2009.

Sanyal, S. K. and Butler, S. J. (2005), "An Analysis of Power Generation Projects from Enhanced Geothermal Systems." *Geothermal Resources Council Transactions*, **29**.

Tester, J. W., et al. (2006), "The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century." INL/EXT-06-11746. Cambridge, MA. Massachusetts Institute of Technology, http://www1.eere.energy.gov/geothermal/future_geothermal.html.

Williams, C. (U.S. Geological Survey) (2009a), Personal communication with C. Augustine, March 30, 2009.

Williams, C. F. (U.S. Geological Survey) (2009b), Personal communication with C. Augustine, April 9, 2009.

Williams, C. F. and DeAngelo, J. (2008), "Mapping Geothermal Potential in the Western United States." *Geothermal Resources Council Transactions*, **32**, 181.

Williams, C. F., Reed, M. J., Mariner, R. H., DeAngelo, J. and Galanis, S. P. J. (2008a), "Assessment of Moderate- and High-Temperature Geothermal Resources of the

United States." Fact Sheet 2008-3082. U.S. Geological Survey, http://pubs.usgs.gov/fs/2008/3082.

Williams, C. F., Reed, M. J. and Mariner, R. H. (2008b), "A Review of Methods Applied by the U.S. Geological Survey in the Assessment of Identified Geothermal Resources." Open-File Report 2008-1296. U.S. Geological Survey, http://pubs.usgs.gov/of/2008/1296/pdf/of2008-1296.pdf.

Young, K. R. and Augustine, C. (2010 (in press)), "Report on the U.S. DOE Geothermal Technologies Program's 2009 Risk Analysis." NREL/TP-6A2-46968. Golden, CO. National Renewable Energy Laboratory.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
February 2010	Conference Paper	

4. TITLE AND SUBTITLE
Updated U.S. Geothermal Supply Curve

5a. CONTRACT NUMBER
DE-AC36-08-GO28308

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
C. Augustine and K.R. Young: NREL
A. Anderson: U.S. DOE

5d. PROJECT NUMBER
NREL/CP-6A2-47458

5e. TASK NUMBER
GT08.3002

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-6A2-47458

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
This paper documents the approach used to update the U.S. geothermal supply curve. The analysis undertaken in this study estimates the supply of electricity generation potential from geothermal resources in the United States and the levelized cost of electricity (LCOE), capital costs, and operating and maintenance costs associated with developing these geothermal resources. Supply curves were developed for four categories of geothermal resources: identified hydrothermal (6.4 GWe), undiscovered hydrothermal (30.0 GWe), near-hydrothermal field enhanced geothermal systems (EGS) (7.0 GWe) and deep EGS (15,900 GWe). Two cases were considered: a base case and a target case. Supply curves were generated for each of the four geothermal resource categories for both cases. For both cases, hydrothermal resources dominate the lower cost range of the combined geothermal supply curve. The supply curves indicate that the reservoir performance improvements assumed in the target case could significantly lower EGS costs and greatly increase EGS deployment over the base case.

15. SUBJECT TERMS
geothermal supply curve; geothermal resources; supply curve data; supply curve analysis; United States; DOE; Geothermal Technologies Program; GTP; electricity generation potential; levelized cost of electricity; LCOE; identified hydrothermal; undiscovered hydrothermal; near-hydrothermal field enhanced geothermal systems; EGS; EGS deployment; reservoir performance; Geothermal Electricity Technology Evaluation Model; GETEM; geothermal technology

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL		19b. TELEPHONE NUMBER *(Include area code)*