U.S. Geothermal Supply Characterization

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ABSTRACT

This paper documents the approach taken to characterize and represent an updated assessment of U.S. geothermal supply for use in forecasting the penetration of geothermal electrical generation in the National Energy Modeling System (NEMS). This work is motivated by several factors: The supply characterization used as the basis of several recent Department of Energy (DOE) forecasts of geothermal capacity is outdated; additional geothermal resource assessments have been published; and a new costing tool that incorporates current technology, engineering practices, and associated costs has been released.

The approach has two main components:

- Characterization - estimates the development and operating costs for specific geothermal reservoir volumes in the subsurface identified in existing databases and source publications.
- Representation - groups and generalizes the costs in a manner suitable for input into NEMS using the Geothermal-Electric Sub-module (GES) input file format.

While the geothermal resource can be considered as a single resource with geographically variable properties and designated by reservoir or system, for convenience, the resulting supply representation incorporates five specific resource types: hydrothermal flash, hydrothermal binary, geothermal fluids coproduced with oil and gas, and two types of Enhanced Geothermal Systems (EGS) resource – convective EGS associated with hydrothermal resources at depths less than 3 kilometers, and conductive EGS potential for depths between 3 and 10 kilometers. This updated supply representation extends supply beyond the traditional three Western regions considered by DOE in the past by including cost and capacity estimates for three midcontinent regions. This representation is based on recently available updated supply estimates for hydrothermal and convective EGS resources, and new estimates for coproduced and conductive EGS resources completed as part of the MIT study of EGS resource supply and costs.

This new representation comprises 126 GW of resource potential nationally: 89 GW across all resource types in the Western regions and 37 GW mostly from coproduced potential in the non-Western regions. The total represented capacity is nearly the same for the Western regions as used in previous recent DOE Office of Energy Efficiency and Renewable Energy (EERE) Government Performance and Results Act (GPRA) benefits assessments. However, the Western region mix among specific resources is different. The updated supply features significantly lower levelized cost of energy (LCOE) for hydrothermal resources and somewhat lower LCOEs for EGS than used previously. Further, the inclusion of a significant amount of relatively low-cost coproduced resource further accentuates these cost differences and contributes to a significant increase in the total amount of geothermal resource that is likely to be technologically and economically accessible in the near through midterm period.

1. Introduction

This report documents the approach taken to characterize and represent the supply of geothermal supply for use in forecasting the penetration of geothermal electrical generation in the National Energy Modeling System (NEMS) and presents the resulting supply in comparison to the representation used in earlier analyses. This approach enables the updated supply information to be incorporated into near- to midterm analysis of the competitiveness of geothermal electricity generation, including, for example, the determination of Government Performance and Results (GPRA) benefits for the Department of Energy (DOE) Geothermal Technology Program (GTP or "the Program"). This resource update was used in a specific competitiveness study still under review by the Program.

The NEMS Geothermal Electric Sub-module (GES), developed in 1992, was first run using data on the capital cost of geothermal power from the IM-GEO application developed in the late 1980s by a team led by Dan Entingh (Entingh et al., 1988). Costed supply curves for geothermal power were developed in 1991 by a team led by Susan Petty (Petty et al., 1992). Information for the supply curves was taken from the two primary published sources available at that time: USGS Circular 790 (Muffler, 1978) and the Bonneville Power Authority study (Bloomquist et al., 1985). Each of the subsequent updates to the geothermal sub-module input data, used in both GPRA and Energy Information Administration (EIA) Annual Energy Outlook (AEO) analyses, were based on the original 1992 study data.

In this paper, the potential electrical output and resource characteristics are developed from published sources and a comprehensive assessment of Enhanced, or Engineered, Geothermal Systems (EGS) carried out by a 12-member panel assembled by the Massachusetts Institute of Technology (MIT) to evaluate the potential of geothermal energy to become a major energy source for the United States. As indicated in the resulting MIT report, “Geothermal resources span a wide range of heat sources from the Earth, including not only the more easily developed, currently economic hydrothermal resources, but also the Earth’s deeper, stored thermal energy, which is available almost anywhere. Although conventional hydrothermal resources are used effectively for both electric and non-electric applications in the United States, they are somewhat limited in their location and ultimate potential for supplying electricity. Beyond these conventional resources are EGS resources with enormous potential for primary energy recovery using heat-mining technology, which is designed to extract and utilize the Earth’s stored thermal energy.”[1] EGS methods have been tested at a number of sites around the world and have been improving steadily. The MIT study also assessed geothermal resources co-produced with oil and gas production. Hot waters contained in oil and gas reservoirs, or coproduced geothermal resources, are normally considered a subset of the identified EGS resources, as permeability enhancement is usually required to optimize dedicated production separate from oil and gas production. Because this paper considers only the coproduced resources available from existing oil and gas wells, coproduced is considered a resource type separate from EGS resources. These resources are accessible with current technology and may be relatively inexpensive to develop because the wells and other resource-related infrastructure are already in place.

While the geothermal resource can be considered as a single resource with geographically variable properties and designated by reservoir or system, for convenience, cost and electrical capacity estimates in the updated supply characterization are organized by five specific resource types: hydrothermal flash, hydrothermal binary, geothermal fluids coproduced with oil and gas, and two types of EGS resource –convective EGS associated with hydrothermal resources at depths less than 3 kilometers, and conductive EGS potential for depths between 3 and 10 kilometers.

The primary purposes of this paper are to document the following:

- The approach taken to updating the characterization of the electrical supply potential of the various geothermal resource types.
- The approach taken to transforming this characterization into a form suitable for use as input to NEMS.
- The resulting supply representation, by resource type and region, in comparison to that used in earlier analyses.

2. General Approach

Figure 1 depicts the general approach, applicable to all five resource types, used to characterize and represent geothermal supply. The overall process has two main components: a characterization activity that identifies the development and operating costs for specific physical volumes in the subsurface identified in existing databases and source publications; and a representation activity that groups and generalizes these costs in a manner suitable for input into NEMS via the GES input file. While the tasks associated with these two components are consistent for all resource types, specific methods used to accomplish each, including assumptions made, differ depending on the resource type and the available source data. These variations by resource type are detailed below.

In the characterization phase, performed by Black Mountain Technology, physical resource characteristics, including depth, temperature, and aerial extent, are first collected and integrated from original sources. These sources vary from databases of identified hydrothermal reservoirs to 3-dimensional slab models of conductive EGS potential calculated for each state. These physical resource characteristics are first used to calculate heat-in-place and recoverable electrical capacity based on specific assumptions, including a recovery factor and other performance factors. The characteristics and calculated capacities are then used as inputs for calculating various component development and operating costs, ultimately expressed as levelized costs of energy (LCOE).

The Program’s Geothermal Electric Technology Evaluation Model (GETEM), a techno-economic systems analysis tool for evaluating and comparing geothermal project cases, is used to compute costs for a set of user-specified input variables that address about four dozen project criteria based on a baseline profile of input values that reflect current technical capabilities and economic conditions. The GETEM tool was developed for the Program by Princeton Energy Resources International (PERI) (Entingh, 2006) under oversight by the National Renewable Energy Laboratory (NREL). The development of GETEM entailed cooperation among key Program researchers at the DOE national laboratories and external consultants, including Idaho National Laboratory (conversion systems, geoscience), Sandia National Laboratory

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[1] Tester et al. (2006), pp. 1-2.

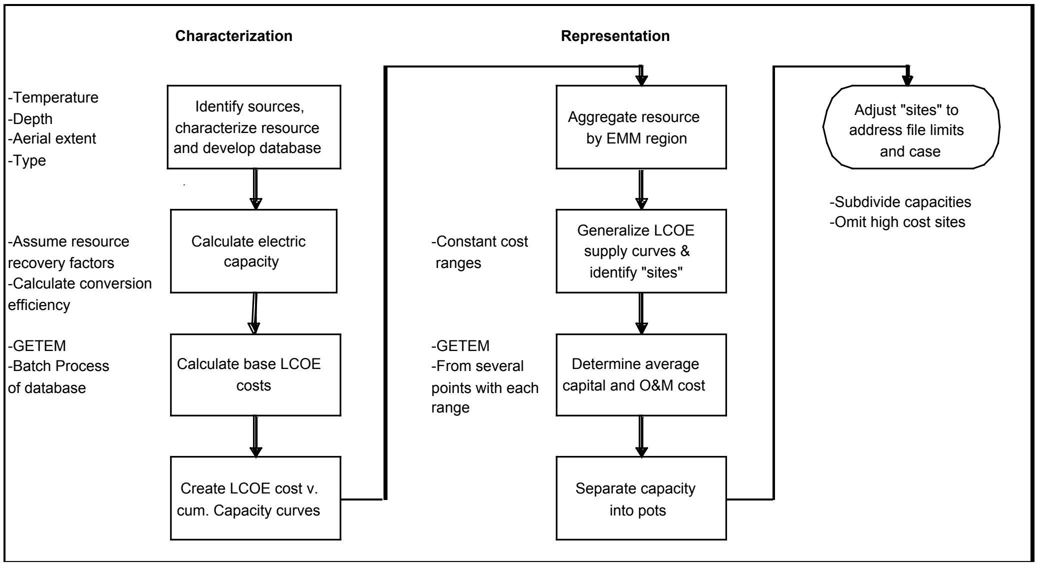

Figure 1. General Approach to Supply Characterization and Representation.

(drilling and wellfield systems), Lawrence Livermore National Laboratory (geoscience), Lawrence Berkeley National Laboratory (geoscience), Black Mountain Technology (geoscience and reservoir engineering), and Livesay Consultants (drilling). While GETEM has recently been reviewed by several individuals in the geothermal industry, a more formal and extensive validation is planned.

The component costs used in GETEM reflect market prices for component equipment, material, and services as of the third calendar quarter of 2004. Some component costs, such as drilling services, have increased significantly since that time, due to an increase in demand for factor inputs associated with oil and gas resource development. For the purposes of this study, these increases are assumed to reflect short-term supply-demand imbalances. Real long run costs are assumed to be in line with the mid-2004 costs used in GETEM.

Costing variables required for input to GETEM are defined from published sources on a site-by-site basis for identified hydrothermal and convective EGS resources. For conductive EGS resources, a similar volumetric recoverable heat approach is used to determine the capacity of this resource. The variables used in calculating the recoverable heat for these resources, such as depth and temperature, are also used as inputs to GETEM for costing. The geothermal resource coproduced from oil and gas reservoirs is characterized by U.S. state, temperature, production rate, and location. This resource data was used as input to GETEM to determine cost. As an example of the output from the characterization phase, Figure 2 depicts national hydrothermal supply using binary and flash plant technology including identified convective EGS sites on the margins of hydrothermal systems, with LCOE as a function of cumulative electrical capacity, characterized using the above component process.

In the representation phase, formulated by Black Mountain Technology, NREL, and OnLocation Inc., the overall approach generalizes the calculated cost and capacity points by region and cost level for input into the GES module. The GES module was developed based on the form of data available from the original study (Petty et al., 1992), which represented the hydrothermal supply only for the western regions of the United States. Petty et al. aggregated individual hydrothermal resources into 51 composite sites with similar capital and operating costs located in a common utility grid region. As a result, GES accepts most of its user-specified inputs via a file keyed by "site." In the input file, each "site" has the following supply-related attributes:

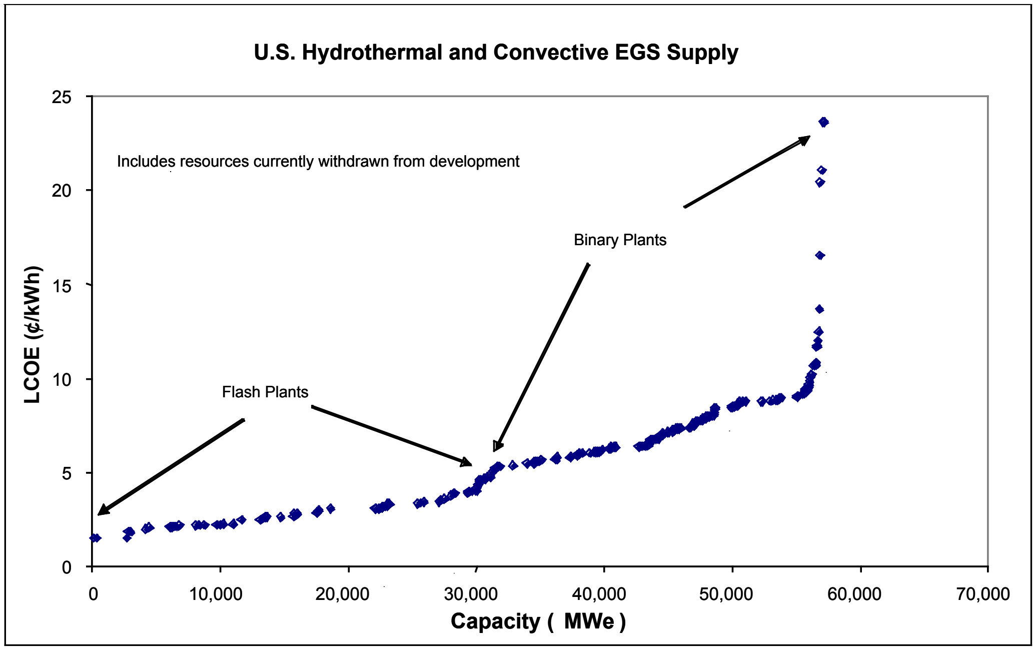

Figure 2. Hydrothermal and Convective EGS Supply for Identified Resources for U.S. The vertical axis identifies the estimated cost of power in 2004$ using a fixed charge rate of 12.8% and cannot be compared to either wholesale generation prices charged to utilities by independent power producers or to actual electricity process paid by consumers. The graph includes 7,300 MWe of mostly flash potential on lands currently withdrawn from development (all with an LCOE less than 5 ¢/kWh). (Source: Black Mountain Technology).

- A NEMS Electricity Market Module (EMM)/ North American Electric Reliability Corporation (NERC) region.
- Costs specified in capital $/kW (in exploration, drilling, wellfield, plant components) and O&M $/kW (field and plant components).
- Four sub-blocks or potential levels of capacity for which multipliers can be specified to adjust individual component capital costs within the NEMS GES code, reflecting cost escalation with progressive site build-out.
- A technology type that references the general conversion technology required to recover the resource. EIA's AEO forecasts are typically based on two conversion types: two-stage flashed-steam and binary. EERE GPRA analyses have been augmented with a third type: EGS.
- Annual capital cost multipliers (applied to each component of capital cost) by year, normally used to reflect industry development experience or Program R&D-driven improvements to costs with time.
- Annual capacities build limits by year in MW/yr, normally used to reflect limitations in the geothermal industry's ability to add capacity.

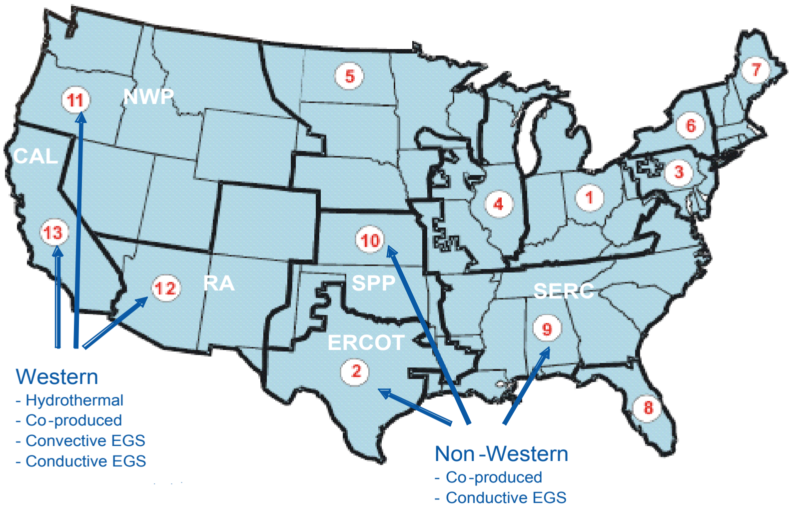

Figure 4. Supply Regions and Resource Types for Updated Supply Representation.

To represent the characterized supply information in the GES input file, the calculated cost and capacity points for a specific resource type are first aggregated by EMM/NERC region. The aggregation from state to region level involves assigning each individual state to a single region (an approximation, as EMM region boundaries do not always coincide with state borders). The resulting supply curve for the region is then visually inspected to identify ranges of capacity that can be generalized as a constant LCOE (a series of constant cost steps, where each step is represented as a "site" in the input file) as depicted for conductive EGS resource for CAL (Region 13) in Figure 3. Component capital and operating costs are then extracted from GETEM output reports for several original cost and capacity points associated with each step. The averages of the respective component costs associated with these points become the cost attributes associated with a composite "site." Additionally, for hydrothermal resource types (both flash and binary), the recoverable capacity value associated with each site is subdivided into the four potential capacity groupings based on the resource characterization source and some simple assumptions, taking advantage of NEMS' ability to assign different cost multipliers to each potential level. Capacities for all other resource types are not blocked – they are all included in the first potential group and are assigned the average cost attributes calculated for the corresponding cost step.

Finally, sites are adjusted to address file limits and specific case requirements and included in an actual input file. Although not an absolute constraint, a 51-site limit, based on the maximum number of sites used in previous GPRA analyses, was observed in constructing the file. The following sites template was initially identified for each region:

- Hydrothermal Flash (distributed across four potential levels)
- Hydrothermal Binary – 1 (lower cost, distributed across four potential levels)
- Hydrothermal Binary – 2 (higher cost)
- Coproduced – 1 (180°C fluids, lower cost)
- Coproduced – 2 (140°C fluids, higher cost)
- Convective EGS
- Conductive EGS – 1 (lowest cost, high temperature/shallow)
- Conductive EGS – 2 (higher cost, high temperature/deep or moderate temperature/ shallow)
- Conductive EGS – 3 (higher cost, moderate temperature/moderate to deep depth)

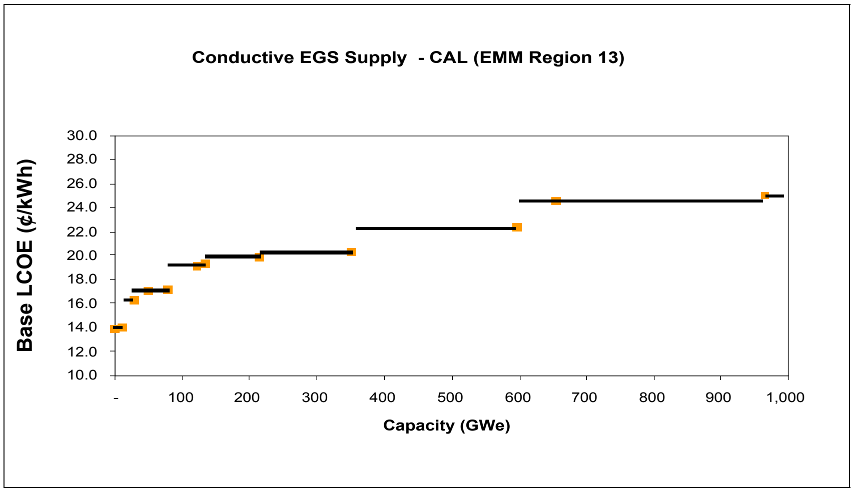

Figure 3. Conductive EGS Supply for CAL (Region 13) for LCOE Costs Up To 25 ¢ /kWh (in 2004$). Squares are individual cost and capacity points from the supply characterization. Black lines are inferred constant costs steps. (Source: Black Mountain Technology).

Table 1 identifies the sites configured for the 13 Lower 48 EMM regions, based on the distribution

Table 1. Geothermal Supply Representation by EMM Region and Geothermal Resource Type. The six regions to which supply is assigned are highlighted in gray.

				Supply "Sites"					
EMM Region #	**Region Abbrev.**	**States**	**# of States**	**Hydro. Flash**	**Hydro. Binary**	**Co- prod.**	**Conv. EGS**	**Cond. EGS**	**Total**
1	ECAR	IA, KY, MI, OH, WV	5	0	0	0	0	0	0
2	ERCOT	TX	1	0	0	2	0	1	3
3	MAAC	DE, MD, NJ, PN	4	0	0	0	0	0	0
4	MAIN	IA, IL, MO, WI	4	0	0	0	0	0	0
5	MAPP	MN, ND, NE, SD	4	0	0	0	0	0	0
6	NY	NY	1	0	0	0	0	0	0
7	NE	CT, MA, ME, NH, RI, VT	6	0	0	0	0	0	0
8	FL	FL	1	0	0	0	0	0	0
9	SERC	AL, AR, GA, LA, MS, NC, SC, TN, VA	9	0	0	2	0	0	2
10	SPP	KS,OK	2	0	0	2	0	0	2
11	NWP	ID, MT, NV, OR, UT, WA, WY	7	1	2	2	1	3	9
12	RA	AZ, CO, NM	3	1	2	2	1	0	6
13	CAL	CA	1	1	2	2	1	3	9
Total		**Lower 48**	**48**	**3**	**6**	**12**	**3**	**7**	**31**
		West	***11***	***3***	***6***	***6***	***3***	***6***	***24***
		Non-West	***37***	***0***	***0***	***6***	***0***	***1***	***7***

Notes: While a total of only 31 "sites" are designated, two issues resulted in an expansion of the number of "sites" to 51 in total. First, sites with total capacities greater than 5,000 MW are subdivided and represented as multiple smaller-capacity sites in the GES input file, in order to reduce the impact of the annual build limit constraint (this approach, applicable to some EGS and coproduced potential, is described briefly in Section 5). Second, some additional "dummy" high-cost sites are added to work around an apparent internal array management problem in NEMS that sometimes results in premature run termination when geothermal supply in a region is close to being completely taken up.

of potential geothermal resources. Only six of the 13 regions are assigned supply (Figure 4): the three Western regions traditionally considered in past supply characterizations (NWP, RA, and CAL), along with three other regions with large geothermal generation potential (ERCOT, SERC, and SPP). Coproduced resources present in very limited supplies in ECAR (1), MAPP (5), and FL (8) are not included in the supply representation. In order to conform to a 51-site limit, conductive EGS resources with costs significantly higher than expected competitive levels are not included in input, effectively limiting representation to four of the six regions, despite the presence of some amount of conductive EGS potential in all 13 regions. The consolidation of all six represented regions is effectively equivalent to a U.S. Lower 48-wide total.

3. Specific Approach by Geothermal Resource Type

Table 2 identifies the specific sources that provide the basis for the physical characterization of geothermal resources. These sources are referred to individually in the discussion of each resource type below (full citations for these sources are included in the References section):

Table 2. Published Sources Used for Physical Characterization of Geothermal Resources.

Source	**Resource Types**	**Text**	**Citation Reference**
United Stated Geological Survey (USGS) Circular 790: Assessment of Geothermal Resources of the United States - 1978	Hydrothermal, Convective EGS	USGS 790	Muffler (1978)
Washington State Energy Office for Bonneville Power Authority (BPA): Evaluation and Ranking of Geothermal Resources for Electrical Generation or Electrical Offset in Idaho, Montana, Oregon and Washington	Hydrothermal, Convective EGS	BPA-NW	Bloomquist et al. (1985)
GeothermEx for California Energy Commission (CEC): New Geothermal Site Identification and Qualification	Hydrothermal, Convective EGS	PIER Study	Lovekin et al. (2004)
Western Governors' Association (WGA) Clean and Diversified Energy Initiative: Geothermal Task Force Report	Hydrothermal, Convective EGS	WGA	WGA (2006)
Nevada Bureau of Mining and Geology (NBMG): Description of Nevada Thermal Springs and Wells by County	Hydrothermal, Convective EGS	NBMG	Garside (1994)
Great Basin Center for Geothermal Energy, University of Nevada Reno: GEOTHERM Great Basin Geothermal Database.	Hydrothermal, Convective EGS	GEO-THERM	Great Basin Center for Geothermal Energy (2005)
U.S. Geological Survey (USGS) Open File Report 99-425: Geothermal Industry Temperature Profiles from the Great Basin	Hydrothermal, Convective EGS	USGS 99-425	Sass et al. (1999)
MIT for GTP: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century	Coproduced, Convective EGS, Conductive EGS	MIT EGS Study	Tester et al. (2006)

While some of the sources provide development cost estimates for some of the sites, these cost estimates were not used in this study. Instead, costs are estimated consistently for all sites and resource types using GETEM. Published costs were compared to those calculated with GETEM, and some limitations were placed on the lower end calculated costs to ensure appropriate alignment. In particular, the costs for hydrothermal resources identified in WGA are generally higher than those calculated with GETEM for use in this study, in part because the WGA costs reflect the rapid increase in drilling costs seen in late 2004 and 2005.

Specific methodologies were used to develop the supply information and the site characteristics for costing the different types of resources considered in this study. Hydrothermal flash and binary and convective EGS resources were assessed on a site-by-site basis. For the coproduced fluids, data on the capacity and characteristics of resources were taken from the recently completed MIT EGS Study. The conductive EGS resource was assessed using data generated by David Blackwell and Maria Richards at the Southern Methodist University (SMU) Geothermal Laboratory as part of the MIT EGS Study. The following section describes the determination of capacities and site characteristics for developing supply curves for each of these three methodologies.

Hydrothermal (Binary and Flash) and Convective EGS Resources

Updated site characterization data is contained in a database that can easily be updated. Sites were characterized by latitude and longitude, state, region, geologic province, temperature, aerial extent of temperature anomaly, depth to reservoir, and estimated or measured flow rate. Other information is also contained in the database which, while not used by the current version of GETEM, may be valuable for improving future cost estimates. This information includes the types and amounts of noncondensable gases present in the geothermal fluids, salinity, present state of development, and installed capacity.

More than 220 individual hydrothermal and convective EGS sites associated with hydrothermal resources were identified from the published sources above. Figure 5 displays the map location of all of the hydrothermal and convective EGS sites on a Google Earth plot. The database was developed starting with the USGS 790 sites with temperatures above 110°C. In this 1978 study, the USGS designated candidate electrical generation sites having temperatures 150°C and higher. Since that time, technology improvements have made possible generation of power from geothermal fluids with temperatures as low as 80°C in special circumstances. This report adopts a cutoff temperature of 110°C based on GETEM code limit, which precludes costing sites with lower temperatures. Sites not in USGS 790, but included in BPA–NW, were added to this database. A number of sites were also added from USGS 99-425 based on temperature-at-depth data from exploration drilling by the geothermal industry during the 1970s to 1980s. Additional sites were added from NBMG. The PIER Study was consulted for updated temperature, depth, and flow rate per well information, but no new sites were found in this database. Similarly, some additional information was obtained from GEOTHERM, but no new sites were added. While the site-by-site database is as complete as possible based on published sources, there is no doubt that additional hydrothermal sites exist. For instance, during the course of this study, a reservoir was discovered at Blue Mountain, Humboldt County, Nevada that is mentioned in the WGA study, but has no obvious surface expression and is not included in the other published sources.

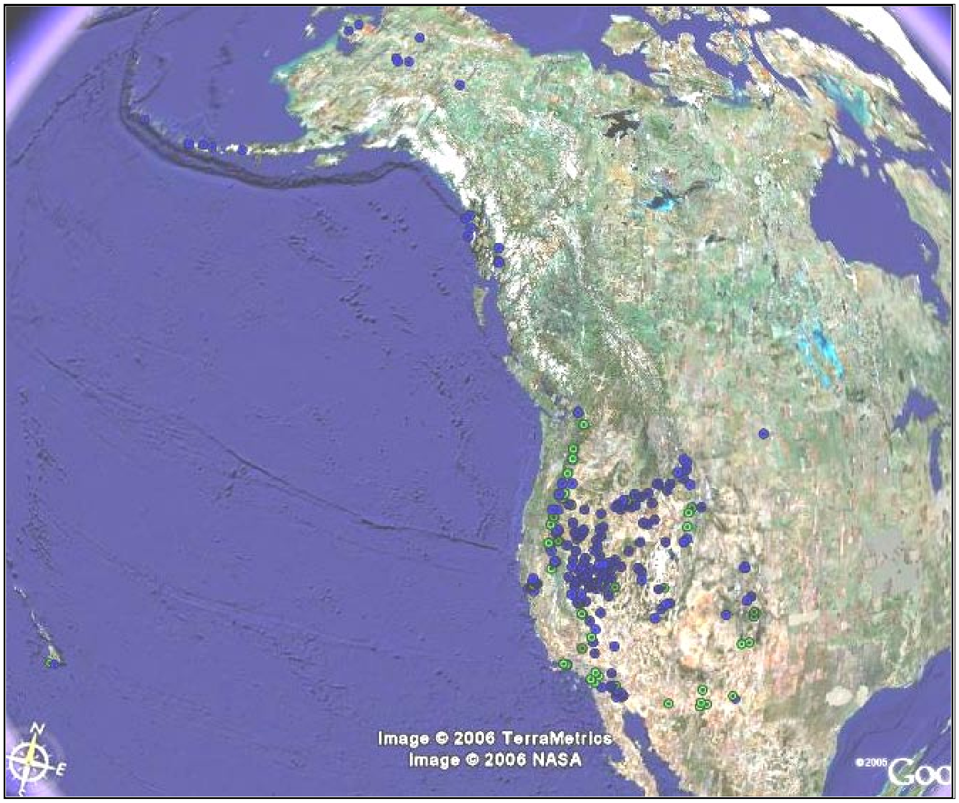

Figure 5. Hydrothermal and Convective EGS Sites Locations in the United States. Hydrothermal sites are shown in blue, convective EGS sites in green. Some of the EGS sites may be overlapped by hydrothermal sites due to the large map scale. While the site database and supply characterization covered the entire United States., only sites in the Lower 48 regions were represented for input to NEMS.

The approach taken in determining the supply available at a site in the database is essentially the same for the hydrothermal and EGS resources (both convective and conductive). This methodology, originally developed by the USGS for Circular 726 in 1976 and subsequently employed in USGS 790, BPA-NW, the PIER Study, and the MIT EGS Study, is based on the concept of a volume of rock containing a total amount of heat. A fraction, the recovery factor, of this heat is potentially recoverable. The thermal energy is then converted to electric power assuming a rejection temperature, or low temperature to which the water will be dropped, a conversion efficiency for the power conversion cycle, and a time over which the energy is assumed to be produced. For USGS 790, the following assumptions were made:

- Recovery factor: 25%
- Rejection temperature: 40°C
- Conversion efficiency: depends on temperature, ranging between 4.5% and 6.0%
- Time period for energy removal: 30 years.

No geothermal resource has been produced to the point where all possible heat has been extracted, so it is impossible to determine realistic recovery factors from actual data. In the end, it is necessary to rely on numerical simulation to predict the final recoverable heat from a resource, until there is adequate data on performance of heat mining operations to compare to these predictions. Numerical simulations by Nathenson (1975), Kruger et al. (2000), Pritchett (1998), and Sanyal and Butler (2005) determine that recovery factors of close to 50% can be expected from circulating fluid in a fractured system. This report adopts a 25% recovery factor, as limiting this recovery in natural systems to half of that predicted for an ideally fractured system seems reasonable. Any further limits on the heat actually recovered should come from other considerations not related to the resource potential.

Supply capacities for hydrothermal systems were taken from USGS 790, where available. If a site was not included in USGS 790, but was included in BPA-NW, the value calculated in the BPA-NW study was used. For sites not included in USGS 790 and BPA-NW, the same methodology used in these studies was used to calculate the power potential. The area and thickness of the temperature anomaly were estimated based on the data available to calculate a volumetric heat-in-place and then a recoverable fraction of that heat as power for 30 years.

The Geothermal Energy Association, an industry trade group, conducted a workshop in 2005 for presentation to the Western Governors' Association to determine the amount of geothermal capacity that might reasonably be expected to be developed over the next 10 years. A group of geothermal experts pooled their available information on the capacity of identified sites, the cost of power from those sites, and the time frame over which they might be developed. The group assigned short-term developable capacities to sites identified in USGS 790. While these capacities were generally smaller than that calculated by the USGS, they represent only the portion of the resource that might be developed quickly in the near term. However, they do represent an assessment of the portion of the resource that might be economic in today's power markets. For this reason, capacities from WGA, where available, were adopted as the hydrothermal capacities. These capacities were then subtracted from the USGS 790 amounts, and the remainder at that site was costed as convective EGS capacity requiring engineering or enhancement to develop, thus increasing the capital and O&M costs for that portion of the capacity at that site.

A value for flow rate per well is a requirement for determining the cost of any geothermal project. There is little actual data on this parameter for any of the resources in USGS 790, because most of the resources have never been drilled and tested. However, there is information on flows from hot springs for some of the sites. This information was used to estimate the potential flow per well based on the range and number of springs, i.e., a large number of small springs or a large flow from a single spring would suggest a permeable reservoir that might have high flow rates per well.

Once the database of sites with temperature, depth, flow, aerial extent of the temperature anomaly, and supply capacity was developed, the cost of power at each site was then calculated using the GETEM model and a batch processing code, which calculated the costs for the entire database. With this batch approach, the costs can be quickly and easily recalculated for the entire database if the data for some sites is updated, new sites are added in the future, or the GETEM code is modified for updated costs.

Conductive EGS Resources

There is little data available on the nature of the rock and the thermal resource that rock contains for depths greater than 3 kilometers. No systematic assessment of the recoverable energy from the heat conducted through the earth's crust under the United States has ever been developed prior to recent efforts reflected in the MIT EGS Study. This section describes the methods used in the referenced study to determine the heat-in-place and the recoverable power from the conductive EGS resource.

Most geothermal wells are drilled to depths less than 3 kilometers. Oil and gas wells may be drilled to greater depths, but they are restricted to areas with potential for oil and gas production. Absent empirical drilling data, the only method available for projecting the temperature of the earth at depth is through determining the heat that flows through the shallow subsurface and then using the nature of the earth materials below to project back to a temperature-at-depth. Over the course of more than 25 years, the SMU Geothermal Laboratory, led by David Blackwell, has been making measurements of terrestrial heat flow across the United States, whenever possible. SMU developed a database of heat flow measurements and then combined this data with knowledge of geology to develop a series of maps of temperature-at-depth. The maps represent the average temperature throughout a 1 km-thick slice beginning at a specified depth. Figure 6, overleaf, depicts the 4.5 km and 6.5 km maps. A thorough description of the method used to develop the maps is included in Chapter 2 of the MIT EGS Study.

The same basic methodology adopted by the USGS and described above was applied. The map areas define 1 km-thick volumes at an average temperature. The heat-in-place is calculated for each 1 km slice using the heat capacity, rock density at that depth, the temperature at depth, and the map-derived volume as described in the hydrothermal resource section above. The rejection temperature assumed for the heat-in-place calculation is the same as that used in hydrothermal section. Heat-in-place calculations were made for five specific temperatures (150°C, 200°C, 250°C, 300°C, and 350°C) at six specific depths (4 km, 5 km, 6 km, 7 km, 8 km, and 10 km).

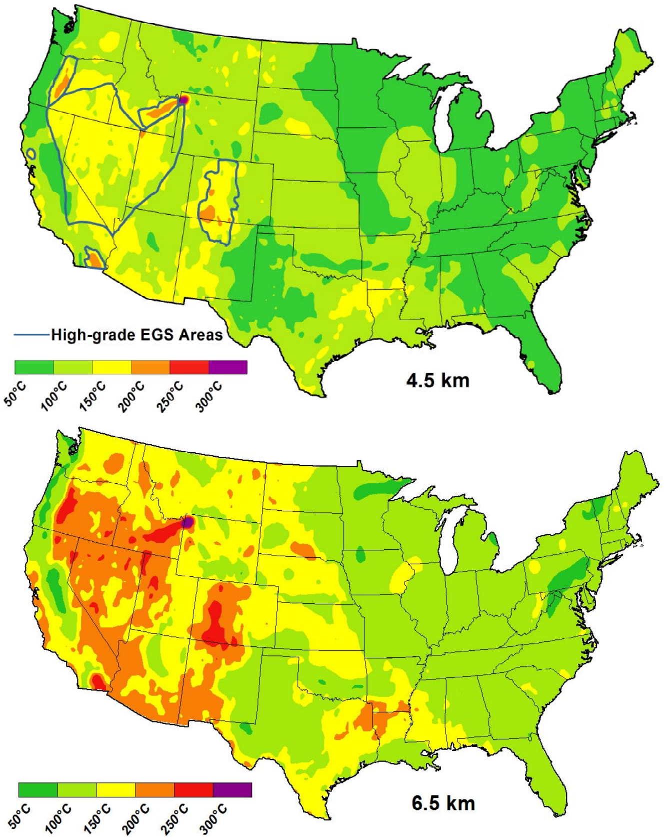

Figure 6. Average Temperature at Depth for U.S. Lower 48, 4.5 km and 6 km. For the 4.5 km map, areas of special conductive EGS interest (150°C or higher) are outlined in blue. (Source: SMU Geothermal Laboratory, 2005).

The recoverable energy from an artificially fractured volume of rock has never been measured. Numerical modeling is the only way to determine what portion of the total heat-in-place might be recovered. Long-term production/injection tests conducted for EGS systems at Fenton Hill, Rosemanowes, and Soultz were used to validate predicted heat recovery from models. Modeling is a reasonable method to determine the best recoverability factor. Sanyal and Butler (2005) have modeled flow in fractured systems to determine the sensitivity of the recoverable heat fraction to several important parameters: rock temperature, fractured volume, fracture spacing, fluid-circulation rate, well configuration, and post-stimulation porosity and permeability. They used a 3-dimensional finite difference model and calculated the fraction of the heat-in-place that could be mined as these important parameters were changed. They found that for a variety of fracture spacings, well geometries, and fracture permeabilities, the percentage of heat recoverable from a stimulated volume of at least 1 x 10^8 m^3 under economic production conditions is nearly constant at about 40%, with a range between 34% and 47%. This recovery factor can be treated as independent of any of these parameters, as long as the stimulated volume exceeds 1 x 10^8 m^3, roughly corresponding to a block of rock 500 m x 500 m x 500 m. Because Phase II of the Fenton Hill project, the Soultz project (both the shallow and deep stimulated volumes), and the Cooper Basin project have achieved fractured volumes based on acoustic emissions mapping of at least 1 km^3 (1 x 10^9 m^3), this volume requirement seems perfectly reasonable to achieve.

With current technology, it is likely that an EGS system can stimulate and access a volume of more than 10^8 m^3. However, there is less control on the fracture spacing and permeability. For this analysis, a value of 20% (half the modeled recovery factor) was used to calculate the supply of power recoverable from the conductive EGS resource.

If a flexible energy-conversion system could be implemented that could use any temperature of fluid to generate electric power or extract usable heat – although at varying efficiency – the rock volume could be cooled significantly while the same surface equipment was used. However, real electric-generating power plants, heat pumps, and heat exchangers are designed for a specific, fairly narrow range of conditions. The larger the difference between design conditions and actual operating conditions, the less efficient the equipment becomes. This efficiency impact places a practical lower limit on the circulating fluid temperature, and consequently, a lower limit on the average temperature of the rock in contact with the fluid. This latter temperature is referred to as the reservoir abandonment temperature. To be conservative, an abandonment temperature only 10°C lower than the initial rock temperature was used in estimating the recoverable energy fraction. If the reservoir rock temperature drops only 10°C on average, there would be ample energy left in the reservoir for future use with replacement equipment designed to operate at lower temperatures. This would increase the sustainability of the reservoir for the longer term. The practice of replacing system components to track declining temperatures may either negatively or positively impact economics for specific sites, depending on long-term normal maintenance and replacement costs if reservoir temperatures were stable.

Following active heat-mining operations, production flow and heat removal would cease, allowing rock temperatures to fully recover by conduction in less than 100 years (Elsworth, 1989). This temperature recovery would permit EGS energy recovery to operate sustainably into the future.

To avoid the problems of determining what power cycle would be most efficient and what rejection temperature would be best to use, this analysis used the net thermal cycle efficiency concept (DiPippo, 2004) and extended it to flash cycles. As with the hydrothermal analysis above, a time of 30 years was used for this analysis.

The resource energy potential was calculated on a state-by-state basis, reduced to reflect surface development constraints (including parks and wilderness areas, Department of Defense lands, and very high elevations) and then apportioned into the EMM/NERC regions.

The cost of power from each depth and temperature was calculated using GETEM and a batch-processing code designed for use with the conductive EGS data. Because the flow rates for an EGS well are a function not only of the geology but also the technology used to enhance the permeability, the per-well flow rate used for costing was based on the highest rate achieved to-date for an EGS project validated with long-term testing. The 25 kg/sec achieved at the Soultz project was used for all EGS resources, including convective resources associated with hydrothermal systems. Flow per well is one of the primary targets for research in EGS technology.

Coproduced Resources

Several studies have been based on the occurrence of fluids at high temperature in some oil and gas producing areas, including:

- Gulf Coast and Midcontinent: McKenna and Blackwell (2005) and McKenna et al. (2005)
- California: DOGGR (2005)

A more comprehensive analysis of the geothermal resource that is actually coproduced with oil and gas, based on the work of Curtice and Dalrymple (2004), is included in the MIT EGS Study. This documents the geothermal fluid produced at temperatures from 100°C to 180°C on a state-by-state basis (Table 3). Calculated capacities in this table assume that all reported produced water production, distributed among thousands of producing wells, is available for use in binary conversion plants, and utilize a rejection temperature of 40°C. Supply capacities for the coproduced resource used in this report are based on three of the four resource temperatures reported in the table: 180°C, 150°C, and 140°C. Values for 140°C and 150°C are combined and treated at 140°C

Capital and O&M costs were estimated using GETEM for the two temperature fluids. Drilling capital costs assume recompletion of existing oil and gas producing wells. Included in this recompletion is the cost of well stimulation through hydraulic fracturing, as well as removal of production tubing and perforation through the hottest water zones in the well to maximize water production. Costs for the wellfield generated by GETEM include the cost of piping. The flow rates assumed for the average production well for this study are low, 38 kg/sec, compared to flow rates for hydrothermal systems. As a result, a large number of wells are needed to make a 30 MW power plant. These factors result in fairly high wellfield piping costs. The same assumption for plant size, per well flow rate, injection pumping, and other wellfield characteristics were used for both the 140°C and 180°C cases. Because produced fluids are assumed to be under normal pressure (i.e., not geopressured), additional equipment is not required for heat recovery and conversion. Because only two discrete temperatures are used, and these fluids are assumed already delivered to the surface

Table 3. Water Production and Potential Power Generation from Oil and Gas Operations for Selected States. Capacities used in this report are shaded in gray. (Source: Tester et al., 2006).

State Abbr.	State	Total Processed Water, 2004 (bbl)	Water Production Rate (kGPM)	Flow Rate (kg/s)	Power@ 100°C (MW)	Power@ 140°C (MW)	Power@ 150°C (MW)	Power@ 180°C (MW)
AL	Alabama	203,223,404	18	1,026	18	47	64	88
AK	Alaska	1,688,215,358	153	8,522	153	389	528	733
AZ	Arizona	293,478	0.0265	1.4814	0.0267	0.0676	0.0918	0.1274
AR	Arkansas	258,095,372	23	1,303	23	59	81	112
CA	California	5,080,065,058	459	25,643	462	1,169	1,590	2,205
CO	Colorado	487,330,554	44	2,460	44	112	153	212
FL	Florida	160,412,148	15	810	15	37	50	70
IL	Illinois	2,197,080,000	199	11,090	200	506	688	954
IN	Indiana	72,335,588	7	365	7	17	23	31
KS	Kansas	6,326,174,700	572	31,933	575	1,456	1,980	2,746
KY	Kentucky	447,231,960	40	2,257	41	103	140	194
LA	Louisiana	2,136,572,640	193	10,785	194	492	669	927
MI	Michigan	188,540,866	17	952	17	43	59	82
MS	Mississippi	592,517,602	54	2,991	54	136	185	257
MO	Missouri	17,082,000	2	86	2	4	5	7
MT	Montana	180,898,616	16	913	16	42	57	79
NE	Nebraska	102,005,344	9	515	9	23	32	44
NV	Nevada	13,650,274	1	69	1	3	4	6
NM	New Mexico	1,214,796,712	110	6,132	110	280	380	527
NY	New York	1,226,924	0.1110	6.1931	0.1115	0.2824	0.3840	0.5326
ND	North Dakota	182,441,238	16	921	17	42	57	79
OH	Ohio	12,772,916	1	64	1	3	4	6
OK	Oklahoma	12,423,264,300	1,124	62,709	1,129	2,860	3,888	5,393
PA	Pennsylvania	18,571,428	2	94	2	4	6	8
SD	South Dakota	6,724,894	1	34	1	2	2	3
TN	Tennessee	62,339,760	6	315	6	14	20	27
TX	Texas	12,097,990,120	1,094	61,067	1,099	2,785	3,786	5,252
UT	Utah	290,427,704	26	1,466	26	67	91	126
VA	Virginia	2,235,240	0.2022	11.2828	0.2031	0.5145	0.6995	0.9703
WV	West Virginia	252,180,000	23	1,273	23	58	79	109
WY	Wyoming	3,809,086,632	344	19,227	346	877	1,192	1,654
US	United States	50,525,782,830	4,569	255,041	4,591	11,631	15,814	21,933
							Total US Coproduced Potential	53,969

via existing infrastructure, the levelized costs for each of the six regions are represented by the same two points, 3.9 ¢/kWh for the 180°C resource and 5.8 ¢/kWh for the 140°C resource ($2004 calculated using a fixed charge rate of 12.8%).

Treatment of Geopressured Resources

Most studies of high-temperature fluids in oil and gas environments have focused on resources in the Gulf Coast states. Some of these resources have very high reservoir pressures, which add to the energy content of the fluids. In addition, high pressures may result in the dissolution of substantial amounts of methane, which can be produced when the pressure is dropped. The heat content of these geopressured resources accessible from existing oil and gas wells is included in the estimates of coproduced resources. Similarly, the heat content of geopressured resources not already producing and occurring at depths greater than 3 kilometers are considered part of the conductive EGS resource estimates. For the purposes of this paper, the kinetic energy and dissolved methane resource associated with the geopressured resource are neglected.

The above costs and capacities of both coproduced and conductive EGS resource are estimated assuming normally pressured fluids. Costs and capacities for the geopressured component of these resources would differ from these initial estimates: Dealing with fluid under pressure and methane might require additional equipment, which would increase costs; while the kinetic energy due to the pressure and chemical energy content of any recovered methane would serve to increase recoverable energy.

Supply Representation to NEMS

Specific approaches were employed to aggregate and generalize the site and state-specific supply characterizations for the hydrothermal and EGS resource types. Table 4 identifies the capacity factors assigned to the resource types as inputs to NEMS. These factors are generally higher than used in previous analyses, particularly for hydrothermal resources exploited with binary conversion technology, and reflect recent operational experience.

Table 4. Assumed Capacity Factors by Technology Type.

Technology Type	GPRA06	Updated Supply
Hydrothermal Flash	0.95	0.90
Hydrothermal Binary	0.80	0.95
Coproduced (Binary)	NA	0.95
EGS (Binary)	0.90	0.95

5. Resulting Supply Representation

The application of the approaches described above to the five types of geothermal resources results in the updated supply representation. This representation is depicted below in two different forms: summary tables that display total capacities by resource type and region (Tables 5 and 6) and figures that display levelized cost supply curves (Figures 7 and 8). These depictions are based on a consistent source: the actual base input (prior to any cost improvement resulting from industry learning or Program R&D), in the form of composite "sites," used for the GES module. In most of the tables and figures in this section, the updated supply representation is compared to GPRA06 Supply, an earlier representation of geothermal supply used in the GPRA analysis for the FY06 Program budget submission.

The capacities in Table 5 reflect the totals included in the updated supply representation of geothermal supply (at various costs) for the five resource types. Represented supply in the three Western regions totals 89 GW across all resource types, with 18% of the capacity having a capital cost below $3,000/kW. The three non-Western regions contribute 37 GW, mostly from coproduced potential, with 40% of the capacity having a capital cost below $3,000/kW. The total national resource capacity represented is 126 GW.

As seen in Table 6, the total represented capacity is nearly the same for the Western regions as that used in GPRA previously (all resource types included). The hydrothermal component of the total national geothermal resource is slightly greater in the updated supply, while the EGS component is almost 30 % less. The balance is made up by the addition of coproduced resources in the updated supply representation.

Figure 7 compares the levelized cost (LCOE) of the aggregate resources types – hydrothermal, coproduced, and EGS – from a national perspective, incorporating the contribution of both capital and O&M costs. LCOEs for both updated supply and GPRA06 Supply representations are computed assuming a fixed charge rate of 12.8%. In the updated supply representation, coproduced resources collectively represent the lowest-cost resources, underlying the curves for the other resource aggregates, reflecting the assumption that this potential can be developed using mostly existing well infrastructure. Hydrothermal resources, requiring wells to be drilled as part of their development, are next in cost for the bulk of their represented capacity. The high-cost tail on the hydrothermal curve reflects the higher potential cost levels associated with lower temperature reservoirs exploited with binary conversion technology.

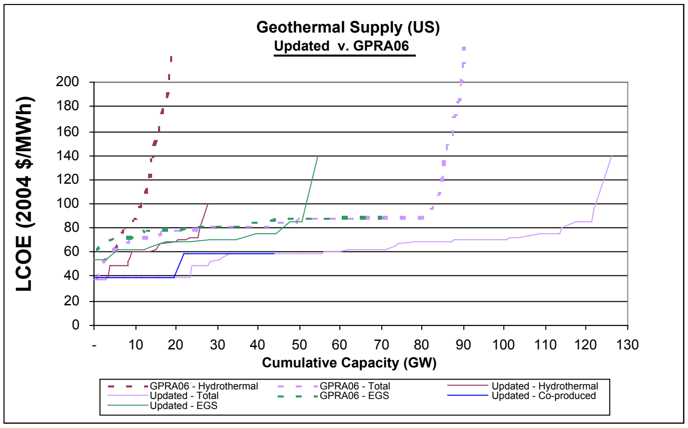

Figure 7. Representation of Levelized Cost (LCOE) of Geothermal Supply for the United States, by Resource Type. Solid lines reflect the updated supply representation, dashed lines the GPRA06 Supply representation used in previous analyses.

Table 5. Updated Supply Representation of Total Capacities of Geothermal Supply for United States and Regions.

	Total Resource Capacities (GW)								
	Non-Western				Western				US Total
	2	9	10	Sub-Total	11	12	13	Sub-Total	
	ERCOT	SERC	SPP		NWP	RA	CAL		
Resource Type									
Hydrothermal (Flash & Binary)	0.0	0.0	0.0	0.0	15.3	0.7	11.6	27.6	27.6
Coproduced	11.8	3.2	18.1	33.2	4.2	1.7	5.0	10.8	44.0
Subtotal (Base Case)	11.8	3.2	18.1	33.2	19.5	2.4	16.6	38.4	71.6
EGS (Associated with HT)	0.0	0.0	0.0	0.0	9.0	6.4	9.4	24.8	24.8
EGS (Conductive)	4.0	0.0	0.0	4.0	23.7	0.0	2.2	25.9	29.9
Subtotal	4.0	0.0	0.0	4.0	32.7	6.4	11.6	50.7	54.7
Total (Program Case)	15.8	3.2	18.1	37.2	52.2	8.8	28.2	89.2	126.3
Cost Characterization									
Resource <$3,000/kW in Capital Cost	5.3	1.4	8.1	14.8	8.5	1.0	6.7	16.1	30.9
Resource < $3,000/kW Share of Total	33%	44%	45%	40%	16%	11%	24%	18%	24%
Resource <$4,500/kW in Capital Cost	11.8	3.2	18.1	33.2	51.3	2.4	26.6	80.3	113.4
Resource < $4,500/kW Share of Total	75%	100%	100%	89%	98%	27%	94%	90%	90%

Table 6. Representation of Total Capacities of Geothermal Supply for United States and Region Aggregates, Updated vs. GPRA06 Supply.

	Total Resource Capacities (GW)					
	Non-Western		Western		US	
	Updated	GPRA06	Updated	GPRA06	Updated	GPRA06
Resource Type						
Hydrothermal (Flash & Binary)	0.0	0.0	27.6	22.2	27.6	22.2
Coproduced	33.2	0.0	10.8	0.0	44.0	0.0
Subtotal (Base Case)	33.2	0.0	38.4	22.2	71.6	22.2
EGS (Associated with HT)	0.0	0.0	24.8	25.0	24.8	25.0
EGS (Conductive)	4.0	0.0	25.9	46.5	29.9	46.5
Subtotal	4.0	0.0	50.7	71.5	54.7	71.5
Total (Program Case)	37.2	0.0	89.2	91.1	126.3	91.1
Cost Characterization						
Resource <$3,000 in Capital Cost	14.8	0.0	16.1	7.2	30.9	7.2
Resource < $3,000 Share of Total	40%	0%	18%	8%	24%	8%
Resource <$4,500 in Capital Cost	33.2	0.0	80.3	83.0	113.4	83.0
Resource < $4,500 Share of Total	89%	0%	90%	91%	90%	91%

EGS resources are the highest cost, partly reflecting the additional cost of stimulation to improve reservoir permeability, but primarily the lower flow rates currently achievable with stimulation technology. The high-cost tail on the EGS curve is the result of including one EGS site for a non-Western region (ERCOT). With the exception of ERCOT, the EGS resources having capital costs greater than $5,000/kW are excluded from the representation, due to the voluntary imposition of a site limit on the input file. Conductive EGS resources are, in addition, generally hampered by high-cost combinations of lower-temperature resources at shallow depths, and higher-temperature resources only at greater depths.

In comparison to the GPRA06 Supply representation, the updated supply representation features significantly lower levelized costs for hydrothermal resources and somewhat lower LCOEs for EGS resources. The significant amount of relatively low-cost coproduced resource is unique to the updated supply representation. In aggregate, the updated supply has a lower levelized cost than GPRA06 Supply throughout the range of cumulative capacity addition. The difference is particularly pronounced in the first 20 GW of potential additions. This lower-cost supply is due largely to technology improvement in the efficiency of flash plants, improvements in technology for reducing reservoir decline, and in the lower costs for O&M due to increased automation.

Figure 8 compares the aggregate national total geothermal supply for the two supply representations (corresponding to "Total" curves in Figure 5) and identifies the contributions of the various resource types to each. In the updated

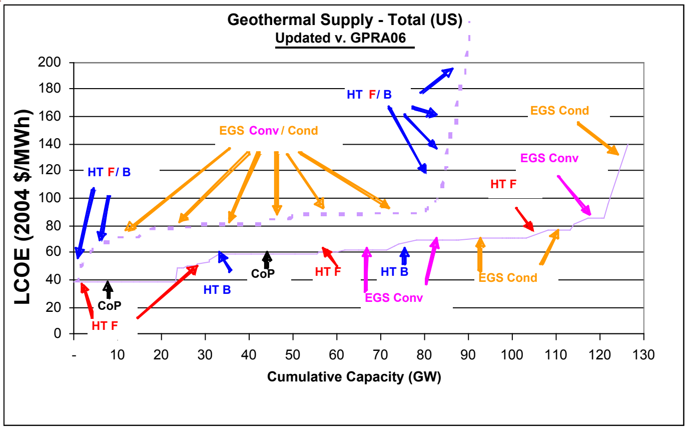

Figure 8. Representation of Levelized Cost (LCOE) of Total Geothermal Supply for the United States. Solid line reflects the updated supply representation, dashed line the GPRA06 Supply representation used in previous analyses. The contribution of specific resource types is noted where "HT F" refers to hydrothermal flash, "HT B" to hydrothermal binary, "CoP" to coproduced, "EGS Conv" to convective EGS, and "EGS Cond" to conductive EGS.

supply representation, hydrothermal (flash and binary) and coproduced resources are the least costly, providing roughly 60 GW of capacity under \$60/MWh (6.0 ¢/kWh). EGS resources, first convective and then conductive, contribute an additional 50 GW costing \$60 to \$80/MWh. By comparison, in the GPRA06 Supply representation, hydrothermal (flash and binary) resources provide a much smaller 10 GW of capacity under \$70/MWh, followed by roughly 70 GW of EGS resources (convective and conductive) for \$70 to \$90/MWh. In this GPRA06 representation, EGS resources occupy the middle, generally flat portion of the supply curve.

The updated supply representation, in aggregate, has a lower levelized cost than previous supply representations and should contribute to a significant increase in the total amount of geothermal resource that is likely to be technologically and economically accessible in the near-term through midterm period.

6. Related Key Model Issues

While the supply representation presented above is the primary geothermal input to GES, there are several other inputs that either impact the LCOE of the supply representation through time or place limits on how much supply can be absorbed in a given period.

First, the cost-reduction impact of technological change is often modeled as the result of two distinct processes: R&D that lowers the cost of specific technology components, and industry learning by doing (LBD) that reduces overall capital costs as a function of increasing cumulative installed capacity. NEMS provides mechanisms to separately incorporate these effects. Either or both of these cost reductions can be applied to the input base supply relations to lower supply costs over time. For the determination of GPRA benefits, the impact of Program R&D is implemented via both capital and O&M multipliers. This "program" case is then compared to a case where only industry learning is assumed.

As an illustration of this latter Program effect on the cost of supply, Figure 9 depicts an example impact of potential improvement for both capital and O&M costs from Program R&D on the levelized cost of geothermal supply for two specific years: 2015 and 2030. In this example, the bulk of the cost improvement is experienced by 2015. The impact of Program improvement between 2015 and 2030 is attenuated by an increase in the fixed charge rate used to compute LCOE (13% in 2015, 13.8% in 2030). This increase is consistent with NEMS assumptions. By 2030, program improvement has reduced the levelized cost by \$5/MWh (5¢/kWh) for the least-expensive resources (up to 25 GW in capacity), by \$10/MWh for the next tier of supply (an additional 35 GW), and by up to almost \$20/MWh for the remaining 60 GW. The application of program improvement also shifts the position of various resource types along the supply curve, in particular shifting EGS resources to the left. As an example, the first block of conductive EGS resources becomes equal in cost (\$48/MWh) to the more costly block of coproduced resources by 2030.

The GES input file also explicitly incorporates a mechanism to provide an upper bound to the amount of capacity added at each specified site in any one year. This mechanism takes the form of an annual build limit that is expressed by site and year. While this feature provides substantial flexibility, it currently replaces an endogenous build control mechanism common to other electricity technologies in NEMS. This mechanism increases capital costs when additions of significant capacity are called for in a short period through the application of an input growth elasticity factor.

The supply representation and these additional inputs determine the cost and capacity of supply available to each region within a given forecast year. Changes in these inputs must be coordinated to achieve credible forecast results. As an example of this need for change coordination, a less costly supply representation by itself will not have a significant impact on penetration if restrictive build limits are in place. Further, if the capacity of supply is increased at individual sites in the input file, some consideration should be given to increasing the build limit proportionally if a modeling goal is to understand the impact of the capacity change on penetration. Alternately, the same effect can be achieved by subdividing high-capacity sites into smaller sites while the build limit is maintained.

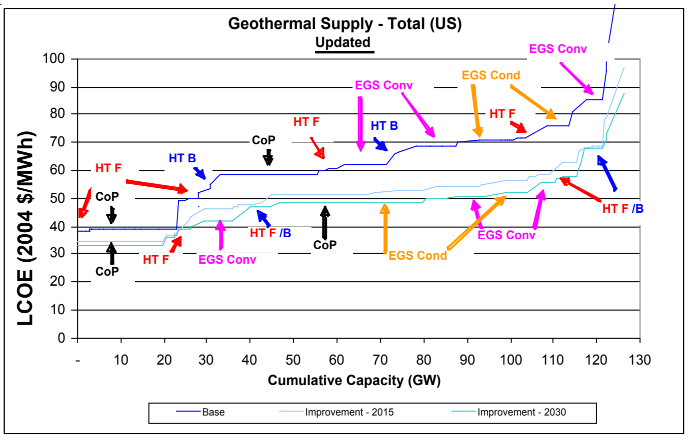

Figure 9. Example Representation of Levelized Cost (LCOE) of Total Geothermal Supply for the United States. (All Resource Types Included). The base updated supply curve from Figure 8 above is depicted in dark blue, along with two example "improved" versions (2015 and 2030) that reflect potential Program improvement impact on both capital and O&M costs. The contribution of specific resource types is noted for the base and 2030 supply curves, where "HT F" refers to hydrothermal flash, "HT B" to hydrothermal binary, "CoP" to coproduced, "EGS Conv" to convective EGS, and "EGS Cond" to conductive EGS.

7. Caveats and Limitations

The lower cost of geothermal supply reflected in the updated supply representation largely results from the impact of technology improvements that have occurred over the past 20 years, including improved efficiency of flash plants, technical gains in reducing reservoir decline, and increasing use of automation in field and plant operations. This lower-cost supply should contribute to a significant increase in the amount of geothermal resource that is likely to be technologically and economically accessible in the near- through midterm (2030) period.

Consistent with NEMS input requirements, the capital and O&M costs identified in the representation of geothermal supply do not include the cost of development financing (NEMS determines financing costs based on its own assumptions). For convenience and accessibility, the represented supply has been depicted above as the levelized cost of supply, which does incorporate the cost of development financing in the form of an assumed fixed charge rate of 12.8%. The depicted levelized supply costs cannot be compared to either wholesale generation prices charged to utilities by independent power producers or to actual electricity prices paid by consumers.

The primary limitation to the approach used to construct the updated supply representation is that it does not directly reflect the uncertainty associated with both costs and capacities. The approach assumes that the development of the full represented capacities of the various types of geothermal resources can be accomplished at the specified capital and O&M costs. A preliminary risk analysis indicates that these expected capacities and costs are conservative. However, given the range of uncertainties estimated, the costs and capacities for coproduced and EGS resources, in particular, are not informed by much actual development and operational experience.

Several existing NEMS limitations were overcome by the supply representation approach. Elimination of these limitations, primarily in the NEMS application code, will reduce the effort necessary to represent future supply updates.

Finally, there are several opportunities for further work to refine both the approach and actual updated supply representation:

- Implement the mostly automated process to update supply information, responding to updates in GETEM baseline cost inputs or algorithms and updates to resource assessments, and timing it to feed the annual AEO and GPRA processes. The data structure described above lends itself to straightforward updating in the future with refreshed technical and economic data.
- Incorporate the results of an updated risk analysis in supply cost and capacity by representing for NEMS input updated characterizations of the 25% and 75% probability supply curves. Alternately, identify more conservative alternate supply scenarios, particularly for coproduced and EGS resources.
- Investigate the potential to revise the supply representation process to identify hydrothermal and convective EGS sites as distinct "sites" in the GES input file. Also, investigate the potential to represent the energy capacities and costs of specific conductive EGS temperature-depth volumes within each state as individual sites. Both approaches would serve to eliminate the generalization step used to represent supply in this analysis and would serve to make the GES input file a more transparent reflection of the specific supply sources.

References

Bloomquist, R.G. et al, 1985. "Evaluation and Ranking of Geothermal Resources for Electrical Generation or Electrical Offset in Idaho, Montana, Oregon and Washington". DOE Technical Report # DOE/BP/13609-3, Washington State Energy Office for Bonneville Power Administration, June 1985. http://www.osti.gov/energycitations/servlets/purl/5632979-icrfaW/5632979.PDF

Curtice, R. J., and E. D. Dalrymple, 2004. "Just the cost of doing business." World Oil, pp. 77-78.

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

DOGGR, 2005. 2004 Annual Report of the State Oil & Gas Supervisor, California Department of Conservation, Div. of Oil, Gas, and Geothermal Resources, Sacramento, p. 197.

Elsworth, D., 1989. "Theory of thermal recovery from a spherically stimulated HDR reservoir." Journal of Geophysical Research, 94 (B2): 1927 - 1934.

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

Entingh, D.J., Petty, S and B. J. Livesay, 1988. IM-GEO: Impact of R and D on cost of geothermal power: Documentation of Model Version 2. 09, Contractor Report Sandia National Laboratory, SAND-87-7018, February, 1988

Garside, L., 1994. "Description of Nevada Thermal Springs and Wells by County" in Thermal Waters of Nevada, Nevada Bureau of Mining and Geology (NBMG) Bulletin 91, 1994.

Geothermal Technologies Program, 2005. "DOE Geothermal Technologies Program Multi-Year Program Plan 2006 – 2011". U.S. Department of Energy, Washington, DC. DOE Internal Planning Document,

Great Basin Center for Geothermal Energy, University of Nevada Reno, 2005. GEOTHERM, Great Basin Geothermal Database. http://www.nbmg.unr.edu/geothermal/geochemdata/geotherm.htm

Kruger, P., Karasawa, H.,Tenma, N., and K. Kitano, 2000. "Analysis of heat extraction from the Hijiori and Ogachi HDR geothermal resources in Japan." Proceedings World Geothermal Congress 2000, pp. 2,677-3,682, Japan.

Lovekin, J., Klein, C., and S. Sanyal, 2004. "New Geothermal Site Identification and Qualification", Public Energy Research Consultant Report #P500-04-051, California Energy Commission, April, 2004. http://www.energy.ca.gov/reports/500-04-051.PDF.

McKenna, J.R. and D.D. Blackwell, 2005. "Geothermal Electric Power from Texas Hydrocarbon Fields", GRC Bulletin, May/June, pp. 121-128.

McKenna, J.R., D.D. Blackwell, C. Moyes, and P.D. Patterson, 2005. "Geothermal Electric Power Supply Possible from Gulf Coast, Midcontinent Oil Field Waters", Oil and Gas Journal, Sept. 5, pp. 34-40.

Muffler, L.J.P., ed., 1978. Assessment of Geothermal Resources of the United States – 1978. U.S. Geological Survey (USGS) Circular 790. http://onlinepubs.er.usgs.gov/lizardtech/iserv/browse?cat=CIR&item=/circ_790.djvu&style=simple/view-dhtml.xsl&wid=750&hei=600&props=img(Name,Description)&page=0

Nathenson, M., 1975. "Physical factors determining the fraction of stored energy recoverable from hydrothermal convection systems and conduction-dominated areas". U.S. Geological Survey (USGS) Open File Report 75-525.

Petty, S., Livesay, B.J., Long, W.P., and John Geyer, 1992. "Supply of Geothermal Power from Hydrothermal Sources: A Study of the Cost of Power for Future Development." Contractor Report Sandia National Laboratory, SAND92-7302, November, 1992.

Pritchett, J. W., 1998. Modeling post-abandonment electrical capacity recovery for a two phase geothermal reservoir. Geothermal Resources Council Transactions, 22, pp. 521-528.

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

Sass, J.H., Priest, S.S., Blanton, A. J., Sackett, P. C., Welch, S. L., and M. A. Walters, 1999. "Geothermal Industry Temperature Profiles from the Great Basin". U.S. Geological Survey (USGS) Open File Report 99-425 Online Version 1.0. http://pubs.usgs.gov/of/1999/of99-425/webmaps/home.html

Southern Methodist University (SMU) Geothermal Laboratory, 2005. U.S. Regional Heat Flow Data Base and Temperature at Depth Maps. http://www.smu.edu/geothermal/heatflow/heatflow.htm

Tester, J.W., Petty, S., Garnish, J., Batchelor, A., Drake, L., and R. Veatch, 2006. "The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century". Massachusetts Institute of Technology (MIT), Cambridge, MA. Final Report to the U.S. Department of Energy Geothermal Technologies Program.

Western Governors' Association (WGA) Clean and Diversified Energy Initiative, 2006. "Geothermal Task Force Report," January 2006. http://www.westgov.org/wga/initiatives/cdeac/Geothermal-full.pdf.