Revisiting the Assessment of Geothermal Resources
<90 °C in the United States

Colin F. Williams, Jacob DeAngelo, and Marshall J. Reed*

U.S. Geological Survey, Menlo Park CA
*deceased

Keywords
Assessment, direct use, electric power, temperature gradient, geothermometer

ABSTRACT

In 2008 the US Geological Survey (USGS) updated the 1979 assessment of the electric power generating potential of geothermal resources in the United States associated with natural hydrothermal systems. These resources are concentrated in the states of Alaska, Arizona, California, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming, which contain all 248 identified hydrothermal systems located on private or accessible public lands and with temperatures greater than 90 °C in the US outside of Alaska and greater than 75 °C in Alaska that have the potential to be exploited for electric power generation. The estimated mean electric power generation potential from identified geothermal resources in the 2008 assessment is approximately 9060 MW-electric (MWe). Of this total approximately 1640 MWe is from systems which fall in the temperature range greater than 90 °C and less than 150 °C. The USGS is completing an updated evaluation of geothermal resources with temperatures less than 90 °C in order to provide a comprehensive look at conventional geothermal resources across the entire temperature range. In this work the estimate of total beneficial heat for these systems is 46,500 MWth, with a total wellhead thermal energy of 94x10¹⁸ J. A potential electric power generating capacity of approximately 400 MWe could be associated with systems in the temperature range 50 to 90 °C, a modest addition to the 9060 MWe estimated for higher temperature systems but one which may have significance in meeting certain local power needs, particularly in remote areas.

Introduction

Geothermal energy resources are characterized by geologic settings, intrinsic properties, and viability for commercial utilization. Comprehensive efforts to assess the geothermal resources of the United States began in the 1970s, and the USGS produced three national geothermal resource assessments in the years following, USGS Circular 726 - Assessment of Geothermal Resources of the United States - 1975 (White and Williams, 1975), USGS Circular 790 - Assessment of Geothermal Resources of the United States - 1978 (Muffler, 1979) and USGS Circular 892 - Assessment of Low-temperature Geothermal Resources of the United States - 1982 (Reed, 1983). These reports evaluated various methodologies for geothermal resource assessments and provided estimates of potential electric power generation that have continued to guide long-term geothermal planning. In 2008 the USGS updated the assessment of conventional geothermal resources in the temperature range above 90 °C and also produced a provisional assessment of EGS potential (Williams et al., 2008a). The 2008 assessment for power generation potential yielded a mean total of 9057 MWe with a 95% probability of 3675 MWe and a 5% probability of 16,457 MWe from 240 identified geothermal systems located in 13 states (Alaska, Arizona, California, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming; Williams et al., 2008a). The assessment also included estimates of undiscovered geothermal resources for the same states in which the identified geothermal systems are located, with the spatial distribution based on a series of Geographic Information
Williams, et al.

Systems (GIS) statistical models for the spatial correlation of geological factors that facilitate the formation of geothermal systems. The mean estimated power production potential from undiscovered resources located on private and accessible public lands was 30,033 MWe, with a 95% probability of 7917 MWe and a 5% probability of 73,286 MWe.

The 2008 assessment did not address geothermal resources below 90 ºC, except for systems in Alaska where the cold environment allows for more efficient power generation at lower temperatures (Williams et al., 2008b). Consequently, revisiting the 1982 assessment provides an opportunity to extend updated assessment results for identified geothermal systems across the entire geothermal temperature range, incorporating both direct use and electric power generation.

Geothermal Resource Assessment Methodology

This paper follows other USGS geothermal resource studies in using the terminology adopted by Muffler and Cataldi (1978) for the subdivision of the geothermal resource base. These subdivisions are easily illustrated through a modified McKelvey diagram (Figure 1), in which the degree of geologic assurance regarding resources is set along the horizontal axis and the economic/technological feasibility (often equivalent to depth) is set along the vertical axis (Muffler and Cataldi, 1978). USGS geothermal assessments consider both identified and undiscovered systems and utilize the following definitions. The “geothermal resource base” is all of the thermal energy in the Earth’s crust beneath a specific area, measured from the local mean annual temperature. The “geothermal resource” is that fraction of the resource base at depths shallow enough to be tapped by drilling in the foreseeable future that can be recovered as useful heat economically and legally at some reasonable future time. Similarly, the “geothermal reserve” is the identified portion of the resource that can be recovered economically and legally at the present time using existing technology (Muffler and Cataldi, 1978; Williams et al., 2008b).

An important component of geothermal resource assessment methodology is the development of geothermal resource models consistent with the production histories of exploited geothermal fields. The primary method applied in USGS assessments for evaluating the production potential of identified geothermal systems was the volume method (Nathenson, 1975; White and Williams, 1975; Muffler and Cataldi, 1978; Muffler, 1979; Williams et al., 2008b), in which the recoverable heat is estimated from the thermal energy available in a reservoir of uniformly porous and permeable rock using a thermal recovery factor, \( R_g \), for the producible fraction of a reservoir’s thermal energy. The basics of the volume method have been discussed in detail elsewhere (Nathenson, 1975; Muffler and Cataldi, 1978; Muffler, 1979; Lovekin, 2004; Williams et al., 2008b), so only a brief summary of the relevant aspects is presented here.

Both the direct use and electric power generation potential from an identified geothermal system depend on the thermal energy, \( q_R \), present in the reservoir and the amount of thermal energy that can be extracted from the reservoir at the wellhead, \( q_{WH} \). Once the reservoir fluid is available at the wellhead, the thermodynamic and economic constraints on geothermal applications can be determined. The challenge in the resource assessment lies in quantifying the size and thermal energy of a reservoir as well as the constraints on extracting that thermal energy. In the volume method, the reservoir thermal energy is calculated as

\[
q_R = \rho C V (T_R - T_0),
\]

where \( \rho C \) is the volumetric specific heat of the reservoir rock, \( V \) is the volume of the reservoir, \( T_R \) is the characteristic reservoir temperature, and \( T_0 \) is a reference, or dead-state, temperature. The thermal energy that can be extracted at the wellhead is given by

\[
q_{WH} = m_{WH} (h_{WH} - h_0),
\]
where $m_{WH}$ is the extractable mass, $h_{WH}$ is the enthalpy of the produced fluid, and $h_0$ is the enthalpy at some reference temperature (15°C in Circular 790). The wellhead thermal energy is then related to the reservoir thermal energy by the recovery factor, $R_g$, which was defined in Circular 790 as

$$R_g = q_{WH} / q_R$$  \hspace{1cm} (3)

Inherent in equations (1) and (2) is a geometrical concept of the reservoir that allows calculation of a volume and an estimate of the ability to extract hot fluid from the volume. In general it is possible to produce many times the original volume of fluid from the reservoir in order to recover the thermal energy from the reservoir rock. In the 2008 USGS resource assessment $R_g$ for fracture-dominated reservoirs was estimated to range from 0.08 to 0.2, with a uniform probability over the entire range. For sediment-hosted reservoirs this range was increased from 0.1 to 0.25 (Williams et al., 2008b). As with the 1982 assessment, the revised evaluation of resources characterized by temperature less than 90 °C has to consider relatively large thermal aquifers for which likely exploitation strategies may not include reinjection to maintain reservoir pressure. Consequently, following Reed (1983), the recovery factor for these resource types is based on a series of models for the optimum well spacing and fluid production from large reservoirs without reinjection.

The new analysis also follows the 1982 assessment in identifying geothermal resources through use of a “minimum temperature function” defined as

$$T_{MTF} = T_s + 10°C + 25z$$  \hspace{1cm} (4)

where $T_s$ is the mean ambient surface temperature and $z$ is depth of the potential geothermal reservoir in km. Systems with temperatures equal to or greater than $T_{MTF}$ are considered “geothermal” and included in the current assessment work.

From estimates of $R_g$ and measurements of reservoir volume and properties, the exergy, $E$, (DiPippo, 2005), referred to as the available work, $\dot{W}_a$, in Circular 790, for a geothermal reservoir can be determined as

$$E = m_{WH} [h_{WH} - h_0 - T_s (s_{WH} - s_0)]$$  \hspace{1cm} (5)

where $s_{WH}$ is the entropy of the produced fluid and $s_0$ is the entropy at the reference temperature. In the actual implementation of this approach the mean values for the input variables are replaced with a range of values corresponding to estimated uncertainties, and these values are then used in Monte Carlo simulations to define the reservoir properties and productivity, along with the associated uncertainties (for example, Muffler, 1979; Williams et al., 2008b). For systems sufficiently hot relative to ambient surroundings to be utilized for electric power generation, the electric energy, $\dot{W}_e$, for a given period of time (typically 30 years) is then determined through multiplying the exergy over the same period of time by a utilization efficiency, $\eta_u$, which is generally well-constrained for a reservoir of a specified fluid state and temperature (Muffler and others, 1979).

$$\dot{W}_e = \dot{E} \eta_u$$  \hspace{1cm} (6)

For power generation above 150°C, Muffler and others (1979) used a constant value for $\eta_u$ of 0.4 down to the minimum reservoir temperature for electric power production of 150 °C. Lovekin (2004) increased this to 0.45. A compilation of $\eta_u$ for existing geothermal power plants producing from liquid-dominated systems over a wide range of temperatures confirms $\eta_u$ equal to approximately 0.4 above 175°C (Williams et al., 2008b). There is a linear decline in $\eta_u$ below 175°C as reservoir temperatures approach the reference state in binary power plant operations. In the 2008 assessment and the work described here the 150 °C lower limit is revised downward to include binary power production from lower temperature systems. Developments in binary power plant technology have led to electric power generation from systems with temperatures as low as 94°C in the lower 48 states (Amedee, California) and 75 °C in Alaska (Chena Hot Springs), and production from lower temperatures is possible, if not always economically viable at the present time. For geothermal systems in the updated assessment, the lower limit for electric power generation is set at 50 °C at which point the average power conversion efficiency approaches zero.

At lower temperatures direct use is typically the preferred application for geothermal water and for the direct use potential Reed (1983) used an updated definition of beneficial heat as

$$Q_{ben} = 0.6\rho C (ka / a_w) Q P (T_s - 25^\circ C)$$  \hspace{1cm} (7)

where the ratio $(ka / a_w)$ is the mean number of wells each reservoir can support according to the reservoir flow analysis specified above, $Q$ is the mass of water produced, and $P$ is the development period. Beneficial heat has units of MWth. This formulation is also applied in the current work to allow for a direct comparison with the results of the 1982 assessment.
Temperature Estimates

In addition to expanding the information available for analysis in the assessment beyond the compilation produced for the 1983 assessment (Reed et al., 1983) through the addition of more recent data compilations (e.g., Lienau and Ross, 1996), the new analysis incorporates a consistent approach to reservoir temperature estimates across the entire range of interest. Geothermal reservoir temperatures can be determined from in situ measurements in exploration and production wells where available, but in order to characterize the thermal state of a geothermal reservoir when in situ temperature measurements are not available, chemical geothermometers can be applied as proxies. The calculation of chemical geothermometers rests on the assumption that some relationship between chemical or isotopic constituents in the water was established at higher temperatures and this relationship has persisted when the water cools as it flows to the surface. The calculation of subsurface temperatures from chemical analyses of water and steam collected at hot springs, fumaroles, geysers, and shallow water wells is a standard tool of geothermal exploration and fills the need to estimate the subsurface temperature of a geothermal prospect area before any deep wells are drilled.

Interpretation of the calculated temperatures requires knowledge of the most likely reactions to have occurred between the water and the surrounding rocks. In addition, the charge balance should be calculated for every water analysis as a check for the completeness of the analysis and its accuracy. For USGS geothermal resource assessments, some simple calculations are used to determine the reliability of the chemical analyses of geothermal waters (Reed and Mariner, 2007). Each ion in the analysis is converted to its equivalent concentration, and the charge balance error (CBE) is calculated as 100 times the absolute value of the difference between the summation of equivalent concentrations of cations (Na+, K+, Ca++, Mg++) and the summation of equivalent concentrations of anions (Cl-, F-, HCO3-, SO4-) divided by the average of the summation of equivalent concentrations of cations and the summation of equivalent concentrations of anions. An error greater than 10 percent in the charge balance is indicative of a problem with the analysis, and analyses that fall into this category are only be used for geothermal calculations in the assessment if no other analyses are available and the associated uncertainties in the calculated temperatures can be quantified.

Geothermometer-based temperature estimates in the USGS geothermal resource assessments rely primarily on silica and cation geothermometers. In natural environments, it is often difficult to choose the correct silica geothermometer because it is not clear which mineral is controlling the dissolved silica concentration. Below 180°C, there is a choice between geothermometers for chalcedony and quartz, since each of these minerals may control the dissolved silica in different rock environments. As noted by Reed and Mariner (2007), the Giggenbach (1992) equation works well to approximate the calculated temperature in the transition zone between the chalcedony solubility control at low temperatures and the quartz solubility control at high temperatures. This smoothed curve eliminates the ambiguity of the calculations between 20°C and 210°C.

The cation geothermometers use ratios of cation concentrations to represent the hydrothermal, steady-state reactions that take place within mineral groups such as the feldspars, micas, zeolites, or clays. The use of concentration ratios rather than the actual concentrations makes these geothermometers less sensitive to changes in strength of the solution due either to boiling or to dilution. The cation geothermometers normally use sodium, potassium, calcium, magnesium, and lithium in various relationships that are temperature dependent. For the Na-K-Ca-Mg geothermometer, these relationships are based on several different mineral equilibria, and these different reactions result in a discontinuous function for this geothermometer and an underreporting in the number of systems in the range between 100°C and 130°C (Reed and Mariner, 2007).
Although control from calibration well samples is limited, it appears that the K-Mg geothermometer provides estimated temperatures reasonably close to temperatures measured in drilled geothermal systems within the 90°C to 130°C range. The potassium-magnesium geothermometer relates temperature to the logarithm of the ratio of potassium concentration squared to magnesium concentration, \( \frac{c(K)^2}{c(Mg)} \). Because the potassium to magnesium ratio is consistently representative of the subsurface temperature, the K-Mg geothermometer is generally the preferred cation geothermometer in current USGS assessments. The Na-K-Ca geothermometer is preferred in Cl-rich waters and used where Mg data are unavailable. The magnesium ion concentration is below the detection limit in many analyses of geothermal waters, and the K-Mg geothermometer cannot be calculated for these waters.

Introduction of the K-Mg geothermometer (not used in the 1983 assessment) and application of a consistent approach to temperature estimates across the entire geothermal temperature spectrum where in situ measurements are unavailable leads to a significant difference in the average temperature for systems examined in both the 1983 and new assessment. Figure 2 shows a histogram of temperature estimates for systems reported by Reed (1983) and also examined in the present work. On average reservoir temperature is higher by 7.2°C, which has a significant different in the overall thermal energy calculations. For the broader temperature range included in both the 2008 and present assessment, the application of this consistent approach results in higher temperatures on average for the systems less than 90°C but lower temperatures for those greater than 90°C (Figure 3), reflecting differences in approach to reservoir temperature estimation between Muffler (1979) and Reed (1983).

**Results**

The new compilation incorporates results from 962 geothermal systems, ranging from individual thermal springs to large thermal aquifers. As with earlier assessments, geothermal resources in this temperature range are dominated by the large thermal aquifers. Although the number of states with geothermal resources as defined by equation (4) is increased to 26 compared to the 13 with conventional geothermal resources characterized by temperatures greater than 90°C, more than half of the resource by total thermal energy is concentrated in California, Idaho, Montana, North Dakota, South Dakota, and Wyoming (Figure 4). Overall there is an increase of more than 50% in both beneficial heat and thermal energy in the new analysis. The new estimate of total beneficial heat for these systems is 46,500 MWt compared to 28,900 MWt in Reed (1983). Similarly, thermal energy is 94x10^{18} J compared to 58x10^{18} J in Reed

![Figure 3. Log plot showing number of systems at a specified temperature for the combined sets of those evaluated by Muffler (1979) and Reed (1983) relative to the estimates in Williams et al. (2008a) and this report up to 200 °C.](image)

![Figure 4. Histograms showing (a) wellhead thermal energy, (b) wellhead exergy, and (c) beneficial heat for each of the states with significant geothermal resources.](image)
Applying the 2008 assessment approach (equations 5 and 6) to estimating electric power generation yields a potential generating capacity of approximately 400 MWe for the systems hotter than 50 ºC, a modest addition to the 9060 MWe estimated for higher temperature systems but one which may have significance in meeting certain local power needs, particularly in remote areas. It should be noted that power generation calculations at these low temperatures are highly sensitive to the specific type of power conversion technology chosen and local temperature conditions for both air and water cooling. Consequently, the 400 MWe estimate should be considered a provisional average pending detailed site-specific analyses.

Summary

By applying a consistent approach to evaluating resources across the full geothermal temperature range, the new analysis provides an opportunity to evaluate the entire conventional hydrothermal resource for the United States. Although geothermal resources are a significant source of renewable energy, they represent a small fraction of the thermal energy that could be exploited in the Earth’s crust. The thermal energy contained within all of the identified geothermal resources, including the estimated thermal energy contained in hydrothermal systems within national parks and other protected public lands, is less than $3 \times 10^{21}$ J, equivalent to approximately 0.1% of the thermal energy in the crust of the United States from 0 to 3km depth and approximately 0.01% of the thermal energy in the crust from 0 to 10km depth. Extracting a larger fraction of this geothermal resource base will require advances in Enhanced Geothermal Systems (EGS) technology.

References