Temperature-At-Depth Maps for the Conterminous U. S. and Geothermal Resource Estimates

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Keywords

Heat flow, EGS, temperature, BHT data, well logs, EGS Protocol

ABSTRACT

A third generation geothermal resource assessment has recently been completed for the conterminous US based on a revised heat flow map using over 35,000 data sites. Improvements include: nearly doubling the number of data points used in the analysis, more detailed thermal conductivity models for temperature-at-depth and heat flow calculations, and addition of a significant number of calibration wells as checks on the bottom hole temperature (BHT) correction. The results increase the accuracy of temperature-at-depth models for the conterminous US. These temperature models are the key input required for evaluating the nonconventional geothermal resources on a regional to sub-regional basis. The new resource assessment was prepared according to a proposed global protocol for estimating Enhanced/Engineered Geothermal Systems (EGS) resource potential. A comparison of the new assessment approach with previous studies is provided, along with a discussion of the differences associated with the revised approach.

Introduction

A new geothermal resource assessment has recently been completed for the conterminous US. Other assessments have been described by Sass and Lachenbruch (1979), Blackwell and Steele (1992), Blackwell et al. (1991), Tester et al. (2006), and Blackwell et al. (2007). Preliminary results of this latest version were described for the eastern US by Frone and Blackwell (2010) and Blackwell et al. (2010b). The new resource evaluation is based on a revised heat flow map that improves upon the Blackwell and Richards (2004) map by more than doubling the total data points, increasing the precision in the thermal conductivity models for temperature-at-depth calculation, and significantly increasing the number of calibration wells used to check the bottom hole temperature (BHT) correction. A key project objective was to increase the accuracy of temperature-at-depth models for the conterminous US as a necessary set of data required for evaluating the nonconventional geothermal resources on a regional to sub-regional basis (EGS, coproduced, geopressure, and low-temperature heat uses for example). A contemporary effort was the development of a standard process (protocol) for evaluating the EGS geothermal potential (Beardsmore et al., 2010). This protocol (version 1.0) is under consideration for acceptance by the International Geothermal Association (IGA) and by the International Energy Agency (IEA) as a procedure for use in the global evaluation of geothermal resources.

Steps in the project included:

1. Generation of a new, more detailed heat flow map by:
   a) adding a significant number of new sites to the existing data set,
   b) evaluating the accuracy of the corrected Bottom Hole Temperatures (BHT) based on additional calibration wells,
   c) developing site specific models of the vertical thermal conductivity section of the upper 5 to 10 km of the crust;
2. Use of the new map to provide more site specific and accurate temperature-at-depth maps for the conterminous US;
3. Calculation of the thermal resource expressed as EGS potential stored in the upper crust (3.5 to 10 km);
4. Comparison of the results of the newly estimated EGS potential to previous estimates and using different estimation techniques.

The previous temperature-at-depth models accessible at Google.org/EGS were included in the Future of Geothermal Energy Report (FGE) (Tester et al., 2006). The process used to generate the temperature-at-depth maps was discussed in Tester et al. (2006), Blackwell et al. (2007) with present relatively minor modifications described by Frone and Blackwell (2010). Alaska and Hawaii are not included due to scarcity of data for those two areas, rather than lack of geothermal potential, as both have existing hydrothermal electrical power production sites.

Revision of Heat Flow Map

A total of 34,802 data sites (some sites are averages of several individual measurements) were used in the new analysis, approximately twice the number used in the 2004 heat flow map (see Figures 1 and 2). The general outlines for regional heat flow and temperature-at-depth are widely known and described by Blackwell et al. (1991, 2007). The temperatures in the upper crust are generally higher in the tectonically active regions of the western US, where the regional heat flow is above the continental average and where many known hydrothermal systems with sufficient temperature and flow to generate electrical power with over 3,000 MW of capacity currently installed. It is clear that a large thermal resource also exists outside these areas, and this study outlines the most favorable regions for development.

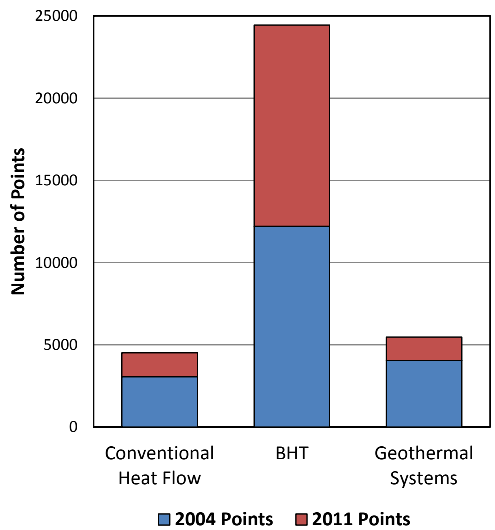

Figure 1. Data number and category comparison for the 2004 and 2011 heat flow maps. The geothermal category includes sites within hydrothermal anomalies that do not reflect regional conditions and were not used in the actual contouring.

The influence of deep Earth conditions on temperatures are shown by the heat flow from below the crustal radioactive layer (upper ~10 km, Blackwell et al., 1991, Roy et al., 1972, etc.) used here with only slight modifications from earlier studies. While this deep Earth heat input dominates the regional distribution of temperature, geothermal development is quite site specific such that the detailed geographic distribution of temperature is important.

The new heat flow and temperature data sites in this report (Figure 2) are primarily derived from temperatures from oil and gas wells measured soon after completion of drilling to a particular depth (referred to as bottom hole temperatures; BHT). Collected from well log headers, these BHT temperatures cannot be used in their raw form; rather, they must be "corrected" to account for the conditions of measurement associated with the drilling activity.

The Harrison Correction, one of several correction methodologies, was applied to the BHT values to represent in-situ conditions. This is the same correction method used previously by Blackwell and Richards (2004) in creating the 2004 Geothermal Map of North America. The Harrison Correction is a second order polynomial correlating BHT measurement to depth. After extensive analysis of various calibration sites where both equilibrium temperature and BHT readings were available, it was decided to standardize on the Harrison Correction method and to establish minimum well depth criteria of at least 600 m, with 1 km or greater preferred. While additional precision equilibrium temperature readings to determine the accuracy of temperature-at-depth interpretations should be collected, the available calibration sites with both equilibrium temperatures and BHT's suggest the corrections to be accurate to ±10 %.

As part of this project, approximately 10,000 new BHT data were collected from well log headers for the states of Pennsylvania, West Virginia, Kentucky, Michigan, Ohio, Illinois, Indiana, Tennessee, Kansas, New Mexico, Colorado and Wyoming and then converted into digital form. The new points were combined with ~10,000 points from an AAPG database partially used in the construction of the 2004 map and another 6141 new points from the state of Texas (Blackwell et al., 2010). Despite the inherent need for corrections and thus the possibility for error, the large quantity of available BHT readings from wells at least 600 m justifies their use. Although conventional heat flow measurements are not subject to drilling fluid correction errors, their relatively shallow average depth of only about 300 m means a much larger temperature extrapolation occurs to the deeper depths. Therefore, the lower quality aspect of the BHT data is offset by the actual measurement at a significant depth that removes some of the uncertainty of the extrapolation needed for the shallow points.

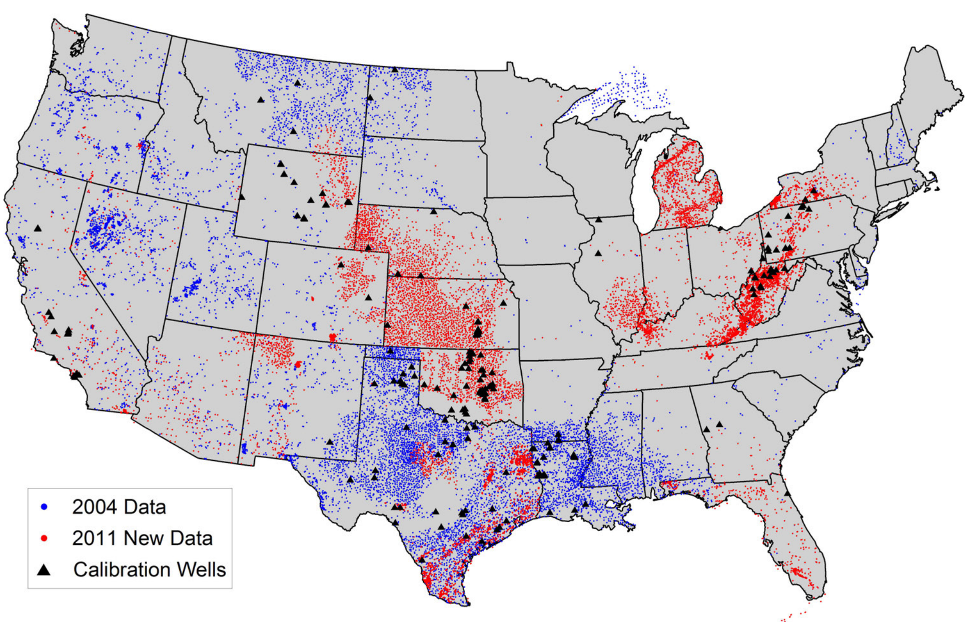

Figure 2. Data Sites for the two studies with calibration (Spicer data and equilibrium well logs) localities shown as Triangles.

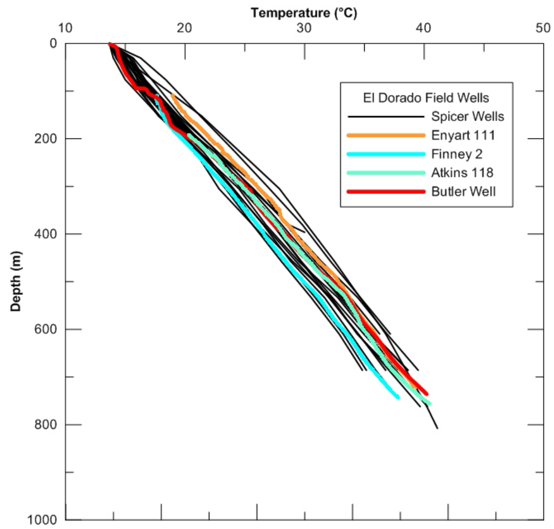

Figure 3. Temperature-depth data for the El Dorado Oil Field, central Kansas. The "Spicer" maximum reading thermometer data are shown as black lines and SMU equilibrium well logging data are shown as color.

In addition to the oil and gas industry data, a legacy data set collected in the 1920s and 1930s (Spicer, 1964) was incorporated for the first time as calibration wells (see Figure 2). Although a few wells from the Spicer data set have been used in the past (Blackwell, 1969; Guffanti and Nathenson, 1981) their usefulness was limited by the difficulty in locating the sites shown on paper copies of old maps of various scales and quality. Through the use of Google Earth, the well locations were identified and digitized to within a reliable radius (few 10's of meters to a few hundred meters). Although old and not widely distributed, this data set proved to be extremely valuable to the project. Unlike modern oil and gas industry BHT readings, these well temperatures were measured in wells at equilibrium conditions at intervals of 250 to 500 ft using maximum reading thermometers. By a stroke of good fortune, it was possible to compare precision equilibrium temperature logs to this data set at the giant El Dorado field in Kansas where two groups had focused special attention years apart. The field, located in central Kansas, has been in continuous production since its discovery in 1918. The comparison of gradients and temperatures for the two data sets appears quite remarkable (see Figure 3) leading to the conclusion that the Spicer data set is of high quality, and can be treated as equilibrium temperature logs.

Another significant set of data included in this study is a reconnaissance thermal gradient data set of 930 'free' holes in the western U.S. acquired by AMAX during the 1980's. These data records, located in the EGI repository in Salt Lake City, Utah, consist of temperature logs made in water wells, mineral exploration holes, and thermal gradient wells in geothermal anomalies with estimations of thermal conductivity based on the lithologies of the wells. A limitation of this data set is that some of the locations in California, Arizona and New Mexico are only approximate (see Williams and Blackwell, 2011) and the original data sheets are not known to exist.

Thermal Conductivity Determination

In addition to adding thousands of new temperature data points and verifying the accuracy of corrections applied to the temperature readings, another key project objective and an important element to the proposed international protocol for estimating global potential for EGS, involves modeling thermal conductivity. Temperature and thermal conductivity are the two key factors in calculating heat flow and temperatures at various depths, which in turn are the basis for estimating EGS potential. The 2011 heat flow map includes increased precision of the basement rock temperature calculations by individual BHT site modeling of the thermal conductivity structure of the overlying sedimentary sections.

The thermal conductivity sections developed for this project allowed calculations for heat flow of previously available BHT

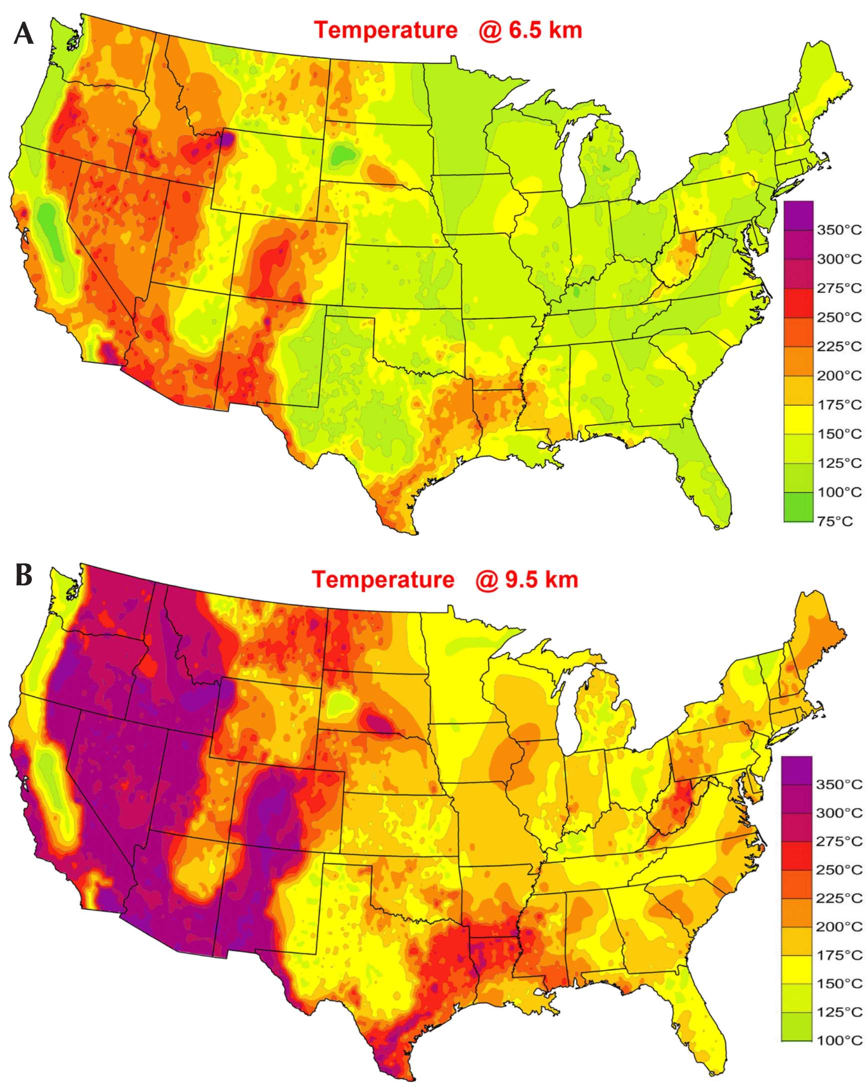

Figure 4. Temperature-at-depth maps for 6.5 km and 9.5 km. These are available online at Google.org/EGS.

data (AAPG, 1994) from Michigan, Illinois, Indiana, Ohio, West Virginia, upstate New York, Kentucky and Tennessee as well as newly acquired data in the Appalachian Basin, the Illinois Basin, and other areas. Lithology sections were also developed in the western states of Nebraska, Kansas, Oklahoma, Wyoming, Colorado, New Mexico and Arizona, where preexisting AAPG BHT data could be added to the heat flow analysis. The thermal conductivity values used in interpreting the section properties came from previous literature within the region, or where unavailable, from the Anadarko Basin (Gallardo and Blackwell, 1999). The COSUNA cross-sectional data (AAPG, 1994) along with the sedimentary thickness were used to develop the thermal conductivity detail. A thickness weighted sum of the well thermal conductivity values was determined for each site. The completion of this task allowed heat flow calculations in the areas where only a handful of conventional heat flow points presently exist (see Figure 2). The result provides an accurate evaluation of the thermal conditions over most of the US so that the EGS geothermal resource potential can be determined on a regional-to-local scale as well as nationally.

Temperature-at-Depth Maps

The temperature and thermal conductivity analysis and resulting heat flow maps were used to create updated temperature-at-depth maps at 6.5 and 9.5 km, as shown in Figure 4. These maps are broadly similar to the previous maps (Tester et al., 2006), but provide much more detail in many areas as illustrated by the map of data sites (Figure 2). When studied in finer granularity, as is possible with many additional data points, local conditions in the eastern two-thirds of the US are found to be hotter than some areas in the western one-third of the US.

Areas of particular interest include the Appalachian trend (Western Pennsylvania, West Virginia, to northern Louisiana), the aquifer heated area of South Dakota, and the areas of radioactive basement granites beneath sediments such as those found in northern Illinois and northern Louisiana. The Gulf Coast continues to be outlined as a huge resource area as confirmed by additional studies (Blackwell et al., 2010a). Another promising sedimentary basin area, the Raton Basin in Colorado, possesses extremely high temperatures and deserves further study (Morgan, 2009; Dingwall and Blackwell, 2011). Thus, in the regionally lower heat flow areas of the eastern two-thirds of the US, there are areas where temperatures are hot enough to support various kinds of geothermal development; in fact, projects to generate electrical power using geothermal energy are already underway in normal heat flow areas such as Wyoming, Mississippi, Louisiana, Texas, and North Dakota.

Resource Estimation

The addition of new temperature data, the improvement in calibration of well log header temperature (BHT) readings, and the new, more detailed thermal conductivity evaluations were all critical elements in creating an updated and improved heat flow map. This updated heat flow map is the basis for the preparation of this third generation assessment of EGS potential in the conterminous US.

There are multiple techniques for determining the potential for power generation from conductive heat flow areas (Sanyal et al., 2002; Tester et al., 2006; Williams et al., 2008). Beardsmore et al. (2010) proposed a protocol currently under consideration by the International Geothermal Association (IEA) to estimate EGS potential in a globally consistent manner. By standardizing on a common set of terminology and format, regional and sub-regional estimates can be compared and aggregated. The new global protocol differs somewhat in terminology and method than the technique used in the resource assessment of EGS by Tester et al. (2006). For comparison purposes, the EGS potential was calculated using the procedure in the Tester et al. (2006) FGE report as well as the proposed global protocol (Beardsmore et al., 2010).

The Protocol is designed to conform closely with the methodology utilized by Tester et al. (2006) to assess the EGS potential of the United States. However, the Protocol departs from that methodology in some details important to this discussion. For example the Protocol explicitly differentiates between 'Theoretical Potential' and 'Technical Potential'. Second, the Protocol is designed to conform to the tenets and terminology of public Geothermal Reporting Codes, with results at different locations and depths classified according to different confidence levels. And finally, the Protocol recommends assessing EGS potential relative to a base temperature using the surface temperature (T_0) + 80°C, rather than relative to just T_0. Williams et al. (2008) found the base temperature fluctuates from 70°C in Alaska to 90°C in high heat flow areas and this impacts the temperature the crust can be reduced to throughout an EGS project. While use of the Protocol provides a globally consistent set of assumptions, estimates of Technical Potential using this Protocol should only be viewed as preliminary until practical experience provides actual data on recoverability of the EGS method.

'Theoretical' Potential of EGS Power in the Upper Crust

The Theoretical Potential is defined as the stored energy in the Earth's crust to a certain depth. The heat stored within a volume of rock is proportional to the temperature, heat capacity (specific heat, C_p), density (ρ) and volume of the rock. In addition, it must be relative to a 'base temperature', which is the lowest temperature to which the rock mass can be reduced. Estimates of EGS Theoretical Potential, therefore, require values for each of these parameters. Beardsmore et al. (2010, Figure 9) provide a flow chart of the five-step process for estimating the Theoretical Potential for EGS to a depth of 10 km of crust.

'Technical' Potential of EGS Power in the Upper Crust

It is impossible to realize the entire Theoretical Potential for EGS power in any location. Rybach (2010) defines 'Technical Potential' is that portion of the 'Theoretical Potential' that can be extracted after consideration of current technical limitations. 'Technical' is defined in the broadest sense, including factors such as land access, rock type, drilling technology, fracture density, stress orientation, regulatory framework, power conversion technology and availability of water. Similarly, extreme depths have higher temperature, but with increased depth, the cost associated with recovery of that resource increases. The Protocol therefore reduces the depth included in the Technical Potential assessment to 6.5 km. Technical Potential seeks to represent an estimate for

EGS that can actually be realized so the national parks and wilderness areas in the western US were excluded in the calculation (Figure 5). In addition in the energy conversion it is assumed that there is only a 10°C drop in temperature. A flow chart for the calculation is shown in Figure 10 of Beardsmore et al. (2010).

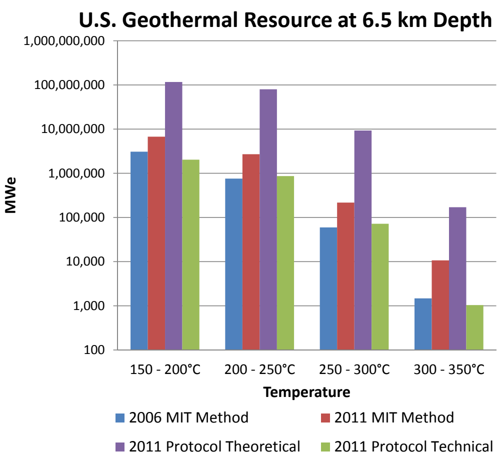

Figure 5a. EGS resource (in MW, vertical axis) to a depth of 6.5 km in different temperature ranges (bottom axis) in the conterminous US. Comparison of calculations based on 4 different approaches is shown.

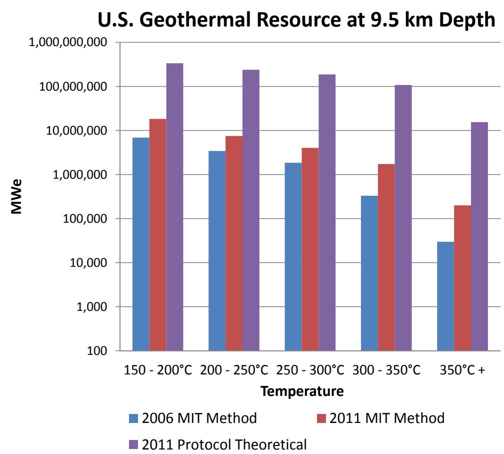

Figure 5b. Heat (in MW for 30 years, vertical axis) to a depth of 9.5 km in different temperature ranges in the conterminous US. Comparison of different calculation approaches as described in the text.

The resource estimate procedure and results contained in Chapter 2 of the FGE 2006 report (Tester el al., 2006) most closely align with the 'Theoretical Potential' Protocol definition while those in Chapter 3 of the report are similar to the 'Technical Potential' definition. However, in both cases the FGE 2006 calculations were carried to a depth of 10 km. The change from the 10 km depth used in the Tester et al. (2006) report to the 6.5 km depth for the potential is one reason for the difference between total values.

Comparisons and Conclusion

The results of the different calculation procedures are compared in Figure 5. Both the Theoretical Potential (total heat) value and Technical Potential for the conterminous U.S. at a particular depth are expressed as MW available over a 30 year period. Figure 5a shows the resource to a depth of 6.5 km. Figure 5b shows the Theoretical Potential from the same analyses to a depth of 9.5 km. At both depths, the purple bar, 'Protocol Theoretical', represents the resource calculation by temperature range using the procedure described by Tester et al. (2006 in Chapter 2) and Blackwell et al.(2007) using the 2006 temperature-at-depth maps. The blue and red bars, 'MIT Method', show the resource calculation using the Tester et al. (2006) Chapter 3 methodology, but with the appropriate temperature-at-depth maps. Key assumptions used in the "MIT Method" of calculating MW for a thirty year period shown in Figure 5 include:

- surface temperature subtracted;
- a 10°C temperature drop in the reservoir (chapter 3);
- an energy conversion efficiency (approximately 10%) and;
- a 14% exploitation factor (Tester et al., 2006 used exploitation values of 2, 14, and 20%).

Thus the resource estimate procedure and results contained in Chapter 2 of the FGE 2006 report (Tester el al., 2006) most closely align with 'Theoretical potential' definition while those in Chapter 3 are similar to 'Technical potential' definition.

In conjunction the larger number of data points, the improved thermal conductivity modeling of the sedimentary lithology resulted in a better match of the predicted to measured temperatures than the generalized sediment thermal conductivity used in the 2006 calculations. Thus, the 2011 MIT calculation is more precise than the 2006 MIT calculation. A direct comparison between the 2006 MIT Method calculation and the 2011 MIT Method calculation highlights an increase in the assessed resource at each of the temperature ranges studied.

The '2011 Protocol Technical' calculation is intended to be the most realistic evaluation of resources available given current understanding for EGS exploitation. The protocol defining 'Technical' Potential considers the practical considerations of drilling, and limits the analysis to the heat available in the top 6.5 km of crust. Thus, the 'Technical Potential' calculation does not appear on the 9.5 km chart (Figure 5b). Key assumptions used in the Protocol 'Technical' method of calculating MW for a thirty year period include:

- a maximum depth of 6.5 km;
- surface temperature subtracted;
- removal of inaccessible lands (national parks, major urban areas, etc.);
- a 10°C temperature drop in the reservoir;
- an energy conversion efficiency (approximately 10%) and;
- a 14% exploitation factor.

There is a small (approximately ½ order of magnitude) net decrease in the 30 year potential when applying the 'Technical Protocol' rather than the MIT Methodology. All the figures are quite comparable. This new 'technical potential' value of over 4 million MW of accessible electrical energy will only increase over time as our ability to improve upon the energy conversion and exploitation factors increase with technological advances and improved techniques.

The total heat resource sums are about 2% of the Theoretical Potential energy. Note that low temperature uses are not considered in this analysis.

Acknowledgements

The SMU Geothermal Laboratory would not have been able to accomplish this research without the funding and the support from Google.org and the Google RE<C Project.

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