



Update to Enhanced Geothermal System Resource Potential Estimate

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Update to Enhanced Geothermal System Resource Potential Estimate

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Abstract

The deep EGS electricity generation resource potential estimate maintained by the National Renewable Energy Laboratory was updated using the most recent temperature-at-depth maps available from the Southern Methodist University Geothermal Laboratory. The previous study dates back to 2011 and was developed using the original temperature-at-depth maps showcased in the 2006 MIT *Future of Geothermal Energy* report. The methodology used to update the deep EGS resource potential is the same as in the previous study and is summarized in the paper. The updated deep EGS resource potential estimate was calculated for rock at depths between 3 and 7 km whose estimated temperature exceeds 150°C. The updated deep EGS electricity generation resource potential estimate is 5,157 GW_e. A comparison of the estimates from the previous and updated studies shows a net increase of 925 GW_e in the 3-7 km depth range, due mainly to increases in the underlying temperature-at-depth estimates from the updated maps.

Introduction

The National Renewable Energy Laboratory (NREL) develops and maintains quantitative estimates of the potential electric power generation capacity of U.S. geothermal resources for the U.S. Department of Energy Geothermal Technologies Office. These estimates are used to characterize and summarize the U.S. geothermal resource base, to develop estimates of the cost of developing geothermal resources, and to generate geothermal supply curves. The supply curves are used as inputs to market penetration models that model the deployment of electric power generation technologies in future years. The geothermal resource potential estimate is broadly split into conventional hydrothermal resources and Enhanced Geothermal System (EGS) resources, and is further subdivided into four categories: identified hydrothermal, undiscovered hydrothermal, near-hydrothermal field EGS, and deep EGS.

The U.S. deep EGS resource potential is defined here as the thermal energy stored in rock at depths greater than 3 km below the Earth's surface and at temperatures exceeding 150°C in the continental United States. The deep EGS resource potential estimate is based on temperature-at-depth maps developed by the Southern Methodist University Geothermal Laboratory (SMU). Both the methodology and the underlying temperature-at-depth maps of the U.S. used to develop the deep EGS resource potential estimate for the U.S. in this study originated in the *Future of Geothermal Energy* report (Tester et al., 2006). The methodology was adopted by NREL and first used to develop supply curves for EGS in (Petty and Porro, 2007). The current resource potential estimate was last updated in (Augustine, 2011), which made improvements to the methods used to account for land exclusions and corrected some errors in the resource potential calculations. All of these studies use the same, original temperature-at-depth maps.

This study uses the most recent set of temperature-at-depth maps from SMU (Blackwell et al., 2011) to update the estimate of the deep EGS resource potential. The methodology used to develop the resource potential estimate is the same as that used in the previous estimates, and is described in below.

Methodology

The methodology used to update the deep EGS resource potential estimate is described in detail in (Augustine, 2011) and is summarized here. The deep EGS resource potential is based on the amount of thermal energy stored in the rock below the Earth's surface. The thermal energy in place for a given volume of rock, Q_{rock} , is calculated from the rock density, ρ , heat capacity, C_p , volume, V , and the average temperature decline of the rock over production, ΔT , as shown in Eq. (1). An average reservoir temperature decline of $\Delta T = 10^\circ\text{C}$ is assumed.

$$Q_{rock} = \rho C_p V \Delta T \quad (1)$$

Only a fraction of the thermal energy stored in the reservoir can be recovered and carried to the surface by circulating fluid through it. This fraction is defined by the recovery factor, R_g , and is assumed to have a value of $R_g = 20\%$ as in previous studies. Eq. (2) shows the amount of recoverable thermal energy, Q_{th} , available for conversion to electricity.

$$Q_{th} = Q_{rock} R_g \quad (2)$$

The recovered thermal energy is converted to electric energy by a power plant at the surface. The potential power capacity of the plant is determined by assuming a plant lifetime over which the energy is extracted from the reservoir and converted to electricity. The conversion efficiency of the power plant is a function of the temperature of the recovered fluid. The conversion of thermal energy to electrical energy, W_e , is calculated from Eq. (3) using an analysis of the net total cycle efficiency, η_{net} , by DiPippo (2004).

$$W_e = \eta_{net} Q_{th} \quad (3)$$

The electricity-generating potential for a given volume of rock is determined by applying Eq. (1)-(3). Table 1 shows the results of these calculations as a function of the EGS reservoir temperature. A plant lifetime of 30 years is assumed. Constant values were assumed for the rock density and heat capacity. The table shows that using this methodology, the amount of recoverable heat is independent of the resource temperature. However, the amount of electricity-generating capacity of the EGS resource is greatly affected by its temperature.

Table 1. Potential Electric Capacity per Cubic Kilometer of Rock for Deep EGS Resources as a Function of Temperature (from Augustine, 2011)

Resource Temp Range	Rock Density	Rock Heat Capacity	Average Reservoir Temp Decline	Heat in Place	Recovery Factor	Recoverable Heat	Plant Life	Plant Efficiency	Potential Electric Capacity
($^\circ\text{C}$)	(kg/km^3)	($\text{kJ}_{th}/\text{kg}\cdot^\circ\text{C}$)	($^\circ\text{C}$)	($\text{MJ}_{th}/\text{km}^3$)	%	($\text{MJ}_{th}/\text{km}^3$)	(years)	%	(MW_e/km^3)
T	ρ_{rock}	C_p	ΔT	Q_{rock}	R_g	Q_{th}		η_{net}	W_e
150-175	2.55E+12	1	10	2.55E+13	20%	5.1E+12	30	11%	0.59
175-200	2.55E+12	1	10	2.55E+13	20%	5.1E+12	30	12.5%	0.67
200-225	2.55E+12	1	10	2.55E+13	20%	5.1E+12	30	14%	0.75
225-250	2.55E+12	1	10	2.55E+13	20%	5.1E+12	30	15%	0.81
250-275	2.55E+12	1	10	2.55E+13	20%	5.1E+12	30	16%	0.86
275-300	2.55E+12	1	10	2.55E+13	20%	5.1E+12	30	17%	0.92
300-325	2.55E+12	1	10	2.55E+13	20%	5.1E+12	30	18%	0.97
325-350	2.55E+12	1	10	2.55E+13	20%	5.1E+12	30	20%	1.08
>350	2.55E+12	1	10	2.55E+13	20%	5.1E+12	30	22%	1.19

Temperature-at-Depth Data

The deep EGS resource potential estimate is made using temperature vs. depth data available from the SMU Geothermal Laboratory. The data consist of maps of the estimated temperature-at-depth in 1-km intervals for the continental United States (Figure 1). The temperature-at-depth maps were originally developed for the *Future of Geothermal Energy* report (Tester et al. 2006) to estimate the EGS resource potential. The original maps are what have been used as the underlying data source for estimating the deep EGS resource potential to date. An update to the temperature-at-depth maps was published in 2011. The update included a significant amount of new heat flow and bottom hole temperature well data, improvements to corrections to bottom hole temperatures, and new models of the thermal conductivity of the Earth's crust (Blackwell et al., 2011). This version of the maps was licensed from SMU and is used here to update the deep EGS resource potential estimate.

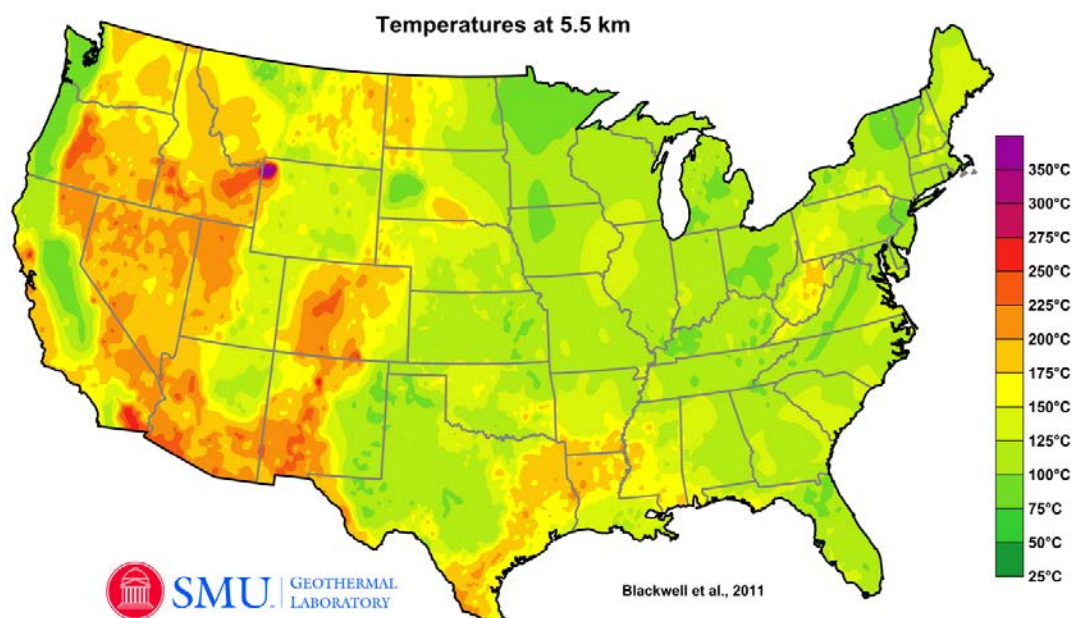


Figure 1. Temperature-at-depth of 5.5 km (from Blackwell et al., 2011)*

Besides new temperature estimates, the updated maps differ slightly from the original versions. First, the temperature data in the updated maps is binned in 25°C increments, whereas the original data was binned in 50°C increments. This gives the new maps higher fidelity, but also requires the data to be re-binned to 50°C to be compared to previous versions of the map.

Second, the original maps are available at depths of 3-10 km (with each 1-km interval map centered at 3.5, 4.5 ...9.5 km), while the updated maps were only licensed at depths of 3-7 km (with maps centered at 3.5, 4.5, 5.5 and 6.5 km, respectively). Because the resource from 7-10 km is not included, the total updated deep EGS resource potential estimate will be smaller than the previous one. However, there is still substantially more resource potential in the estimate than is ever likely to be deployed. Additionally, the excluded depth ranges are near or beyond the

*Temperature-at-depth maps available at <http://www.smu.edu/Dedman/Academics/Programs/GeothermalLab/DataMaps/TemperatureMaps>

depth limit of most wells typically drilled today. Because of this, the U.S. Geological Survey (USGS) limited their EGS resource potential estimate of the Western U.S. to 6 km (Williams et al., 2008). Because of the cost of drilling to such depths, the development cost estimates for these resources is higher than for shallower resources, and experience working with the deep EGS supply curves has shown that resources at these depths are rarely if ever deployed in market penetration models. Therefore, the exclusion of the resource beyond 7 km depth will not significantly impact how the resource potential estimate is used.

A comparison of the temperature-at-depth data from the original and updated SMU maps is shown in Figure 2. Areas in red indicate where the temperature estimate increased, while areas in blue indicate where the temperature estimate decreased. As mentioned above, the updated maps had to be re-binned to 50°C increments to generate the figure and make the comparison. Many of the changes occur where the maps transition from one temperature bin to the next, likely due to small changes in the location of these transitions on the updated maps. However, the figure also shows large areas where the temperature estimate changed due to improvements in the underlying data. One notable example is the West Virginia thermal anomaly, where the temperature was found to be significantly higher than previously thought during a study of bottomhole well temperature data that was incorporated into the updated SMU maps (Frone and Blackwell, 2010; Frone et al., 2015).

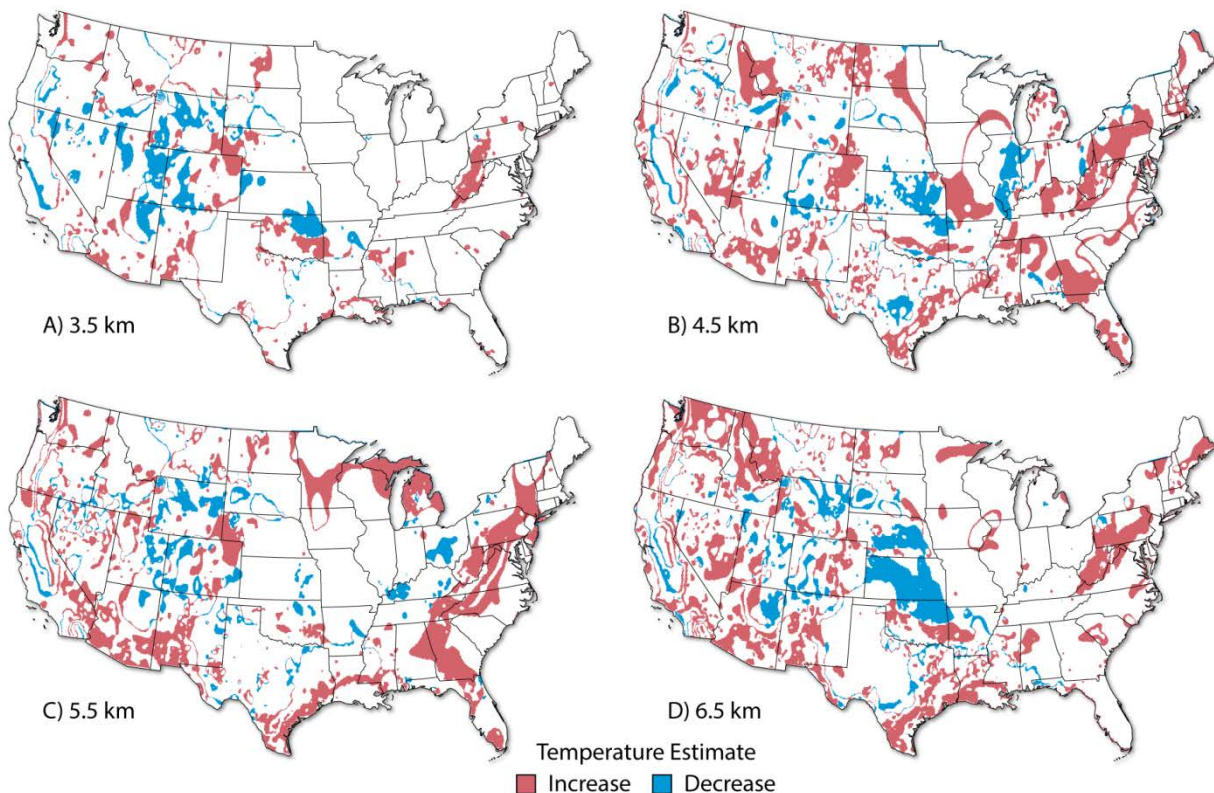


Figure 2. Comparison of temperature-at-depth estimates from original (Tester et al., 2006) and updated (Blackwell et al., 2011) SMU maps. Areas in red indicate where the temperature estimate increased, while areas in blue indicate where the temperature estimate decreased.

Results

The areal extent of each temperature bin above 150°C for each map (depth) was determined from the maps using GIS methods. Federally protected and U.S. Department of Defense (DOD) lands were excluded as in the prior resource estimate (Augustine, 2011). The resulting rock volume for each temperature bin at each depth interval was multiplied by the corresponding volumetric potential electric capacity in Table 1. The reservoir is assumed to extend to the bottom of each 1-km slice, so that the resource estimate for the rock centered at, for example, 3.5 km is for a reservoir that extends from 3 to 4 km. The resulting EGS electricity potential for the continental United States for each temperature/depth interval is shown in Table 2.

Table 2. Updated Deep EGS Electricity Generation Potential (MW_e) for Continental United States Binned by Temperature and Depth Intervals

Deep EGS Electricity Generation Potential (MW _e)										
		Resource Temperature (°C)								
		150-175	175-200	200-225	225-250	250-275	275-300	300-325	325-350	>350
Depth (km)	3-4	74,217	2,592	100	-	-	-	-		
	4-5	740,466	233,228	11,886	325	84	32	-		
	5-6	517,601	724,689	373,680	57,281	4,654	195	128		
	6-7	635,384	491,641	700,330	453,610	120,677	12,116	1,883	0	157

The resource estimate identifies a total of 5,157 GW_e of electricity producing potential. This is significantly less than the 15,847 GW_e estimate from the previous estimate, but as mentioned above, this is due to the exclusion of the resource from 7-10 km. A direct comparison of the previous and updated estimates by temperature and depth interval is shown in Table 3. To make this comparison, the updated resource estimate had to be re-binned into 50°C intervals. This was done by summing the appropriate columns in Table 2. The bottom of the table shows the difference by temperature and depth interval for the two studies, with negative numbers in parentheses and red text. The updated study has a net increase over the previous study of 925,023 MW_e in the 3-7 km depth range that it covers. Some of this is due to the higher fidelity of the temperature binning in the new map, but the majority is due to changes in the underlying temperature estimate.

Table 3. Comparison of previous (Augustine, 2011) and updated (this study) deep EGS resource potential estimate. Updated estimate was re-binned to 50°C to make the comparison. Bottom table shows the numeric difference between estimates, with negative numbers in red.

Electricity Generation Potential (MW _e) - Previous (Augustine, 2011)						
		Resource Temperature (°C)				
		150-200	200-250	250-300	300-350	>350
Depth (km)	3-4	91,516	117	-	-	-
	4-5	590,763	26,526	134	-	-
	5-6	1,139,749	227,969	7,680	50	-
	6-7	1,337,049	723,692	86,057	631	-
	7-8	1,539,597	1,129,434	345,285	32,964	320
	8-9	1,881,116	1,159,750	761,653	138,204	9,922
	9-10	1,907,066	1,251,474	1,015,937	433,749	69,298
Electricity Generation Potential (MW _e) - Updated (This Study)						
		Resource Temperature (°C)				
		150-200	200-250	250-300	300-350	>350
Depth (km)	3-4	76,809	100	0	0	0
	4-5	973,693	12,210	116	0	0
	5-6	1,242,290	430,961	4,850	128	0
	6-7	1,127,025	1,153,940	132,793	1,883	157
Electricity Generation Potential (MW _e) - Difference						
		Resource Temperature (°C)				
		150-200	200-250	250-300	300-350	>350
Depth (km)	3-4	(14,707)	(17)	0	0	0
	4-5	382,930	(14,316)	(18)	0	0
	5-6	102,541	202,992	(2,830)	78	0
	6-7	(210,024)	430,248	46,736	1,252	157

Conclusions

The deep EGS electricity generation resource potential estimate maintained by NREL was updated using the most recent temperature-at-depth maps available from SMU. The update was made using the same methodology as in previous studies, which calculates the thermal energy in place in the subsurface, assumes that 20% of this thermal energy can be recovered, and then converts the thermal energy into electricity generation potential using a correlation for power plant efficiency that is a function of the resource temperature. The updated SMU maps differ from the previous maps in two ways. First, they bin the temperature estimates in 25°C increments instead of 50°C increments as in the original maps. Second, the maps only cover depths of 3-7 km, while the originals cover depths of 3-10 km. The updated deep EGS geothermal resource potential is 5,157 GW_e. This is significantly less than the previous estimate of almost 16,000 GW_e, but this is entirely due to not including EGS resources in the 7-10 km depth interval. A comparison of the estimates from the previous and updated studies shows that the updated study actually has a net increase of 925 GW_e in the 3-7 km depth range that it covers, due mainly to increases in the underlying temperature-at-depth estimates from the updated SMU maps.

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