Assessment of Moderate- and High-Temperature Geothermal Resources of the United States

Scientists with the U.S. Geological Survey (USGS) recently completed an assessment of our Nation's geothermal resources. Geothermal power plants are currently operating in six states: Alaska, California, Hawaii, Idaho, Nevada, and Utah. The assessment indicates that the electric power generation potential from identified geothermal systems is 9,057 Megawatts-electric (MWe), distributed over 13 states. The mean estimated power production potential from undiscovered geothermal resources is 30,033 MWe. Additionally, another estimated 517,800 MWe could be generated through implementation of technology for creating geothermal reservoirs in regions characterized by high temperature, but low permeability, rock formations.

Geothermal power plants at The Geysers in northern California. Currently, the United States has an installed and utilized power production capacity of more than 2,500 Megawatts-electric (MWe) from geothermal plants located in Alaska, California, Hawaii, Idaho, Nevada, and Utah. (USGS photograph by Julie Donnelly-Nolan.)

Introduction

The U.S. Geological Survey (USGS) has recently assessed the electric power generation potential of conventional geothermal resources in the United States. 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 241 identified moderate-temperature (90 to 150°C; 194 to 302°F) and high-temperature (greater than 150°C) geothermal systems located on private or accessible public lands. (Geothermal systems located on closed public lands, such as national parks, were not included in the assessment.) Electric-power potential was also determined for seven low-temperature (less than 90°C) systems in Alaska for which local conditions make electric power generation feasible. In addition, the assessment also includes a provisional estimate of the power generation potential from the application of unconventional, Enhanced Geothermal Systems (EGS) technology in Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming. This assessment benefited from cooperation and coordination with the Department of Energy (DOE); Bureau of Land Management (BLM); the University of Nevada, Reno; the University of Utah; Idaho National Laboratory; Lawrence Berkeley National Laboratory; state and local agencies; and the geothermal industry.

Identified Geothermal Systems

Currently, the United States has an installed and utilized power production capacity of more than 2,500 Megawatts-electric (MWe) from geothermal plants located in Alaska, California, Hawaii, Idaho, Nevada, and Utah. The nearly 15,000 Gigawatt-hours (GWh) of geothermal power generated in 2005 constituted 25% of domestic nonhydroelectric renewable electrical power generation. (Power generation of 1 MWe provides 8.77 GWh of electricity in 1 year.) The results of the new assessment for the power generation potential from identified geothermal systems yield a mean total of 9,057 MWe

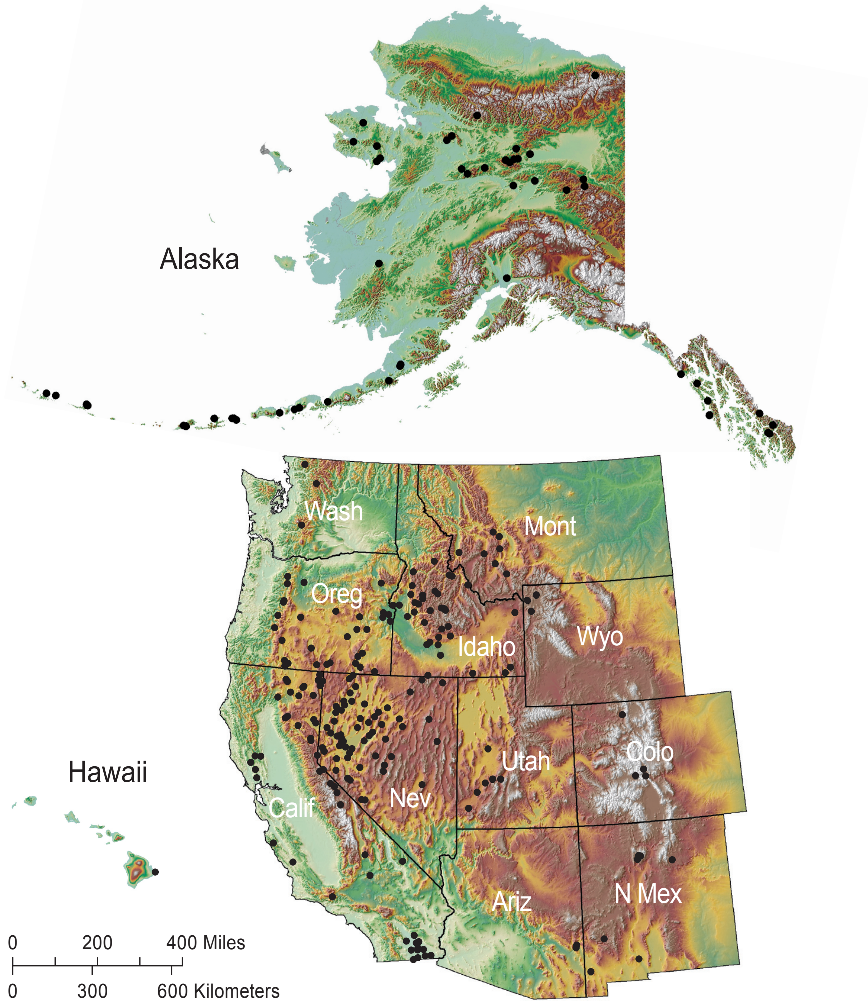

Figure 1. *Map showing the location of identified moderate-temperature and high-temperature geothermal systems in the United States. Each system is represented by a black dot.*

with a 95% probability of 3,675 MWe and a 5% probability of 16,457 MWe (table 1). The distribution of the individual systems across the study area is shown in figure 1. State totals were derived from summations of volumetric models for the thermal energy and electric generation potential of each individual geothermal system (Muffler, 1979; Williams and others, 2008). The results of the assessment indicate that full development of identified systems alone could expand geothermal power production by approximately 6,500 MWe and to seven additional states. The distribution of identified geothermal resources among the 13 states with identified geothermal resources is shown graphically in figure 2*A*. California, with large producing geothermal fields at The Geysers, the Salton Sea, and Coso, has 59.7% of the total resource, followed by Nevada with 15.4% and Alaska with 7.5%.

Undiscovered Geothermal Resources

Undiscovered geothermal resources were assessed for the same states in which the identified moderate- and high-temperature geothermal systems are located, based on a series of Geographic Information Systems (GIS) statistical models for the spatial correlation of

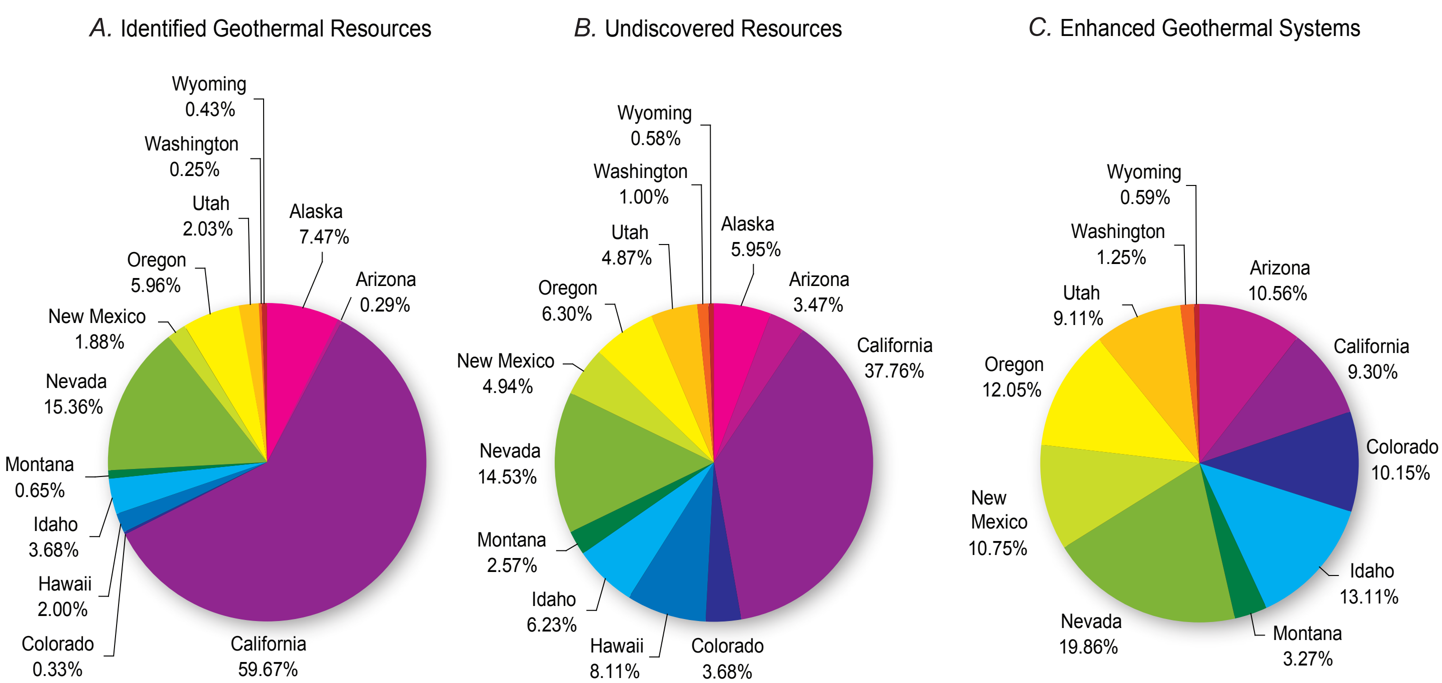

Figure 2. *Pie charts illustrating the distribution of (*A*) identified, (*B*) undiscovered and (*C*) Enhanced Geothermal Systems (EGS) resources (mean estimates) among the western states. Alaska and Hawaii were not included in the assessment of EGS resources because of a lack of information in those states.*

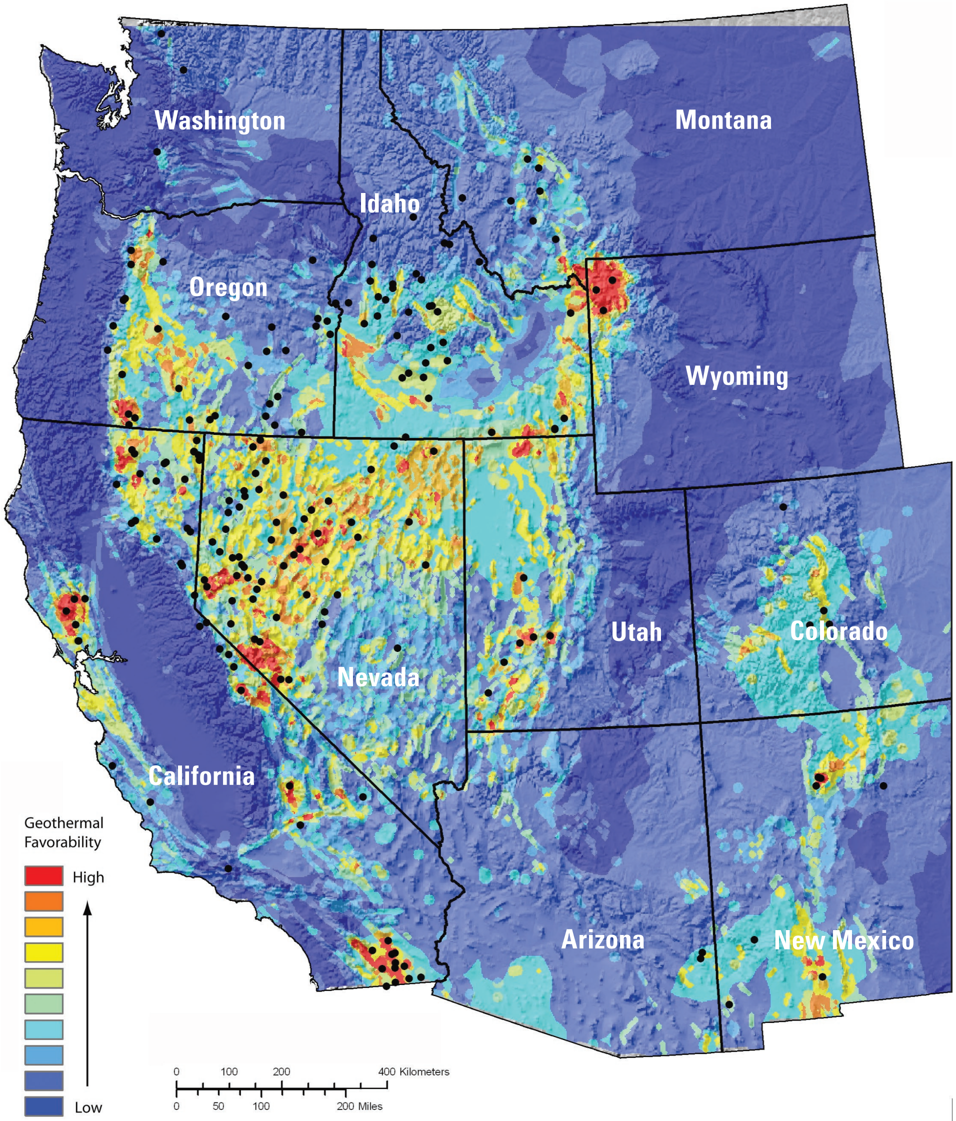

Figure 3. *Example map from one of a series of 28 spatial models showing the relative favorability of occurrence for geothermal resources in the western contiguous United States. The other models differ in details but show generally similar favorability patterns. Warmer colors equate with higher favorability. Identified geothermal systems are represented by black dots.*

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 is 30,033 MWe, with a 95% probability of 7,917 MWe and a 5% probability of 73,286 MWe. As illustrated in figure 2*B*, compared to the identified resources, a larger fraction of the undiscovered geothermal resources are located outside California. This reflects both the limited degree of exploration and development in States other than California and Nevada and the uniqueness of the vapor-dominated geothermal reservoir at The Geysers in northern California, which contributes approximately 1,000 MWe to the identified geothermal resource for the State but is unlikely to be matched by any equivalent occurrences on private or accessible public lands elsewhere in the United States. The undiscovered resources results indicate that additional exploration could add substantially to the total of identified geothermal resources and further expand geothermal power production. As indicated by the geothermal favorability map shown in figure 3, regions with significant geothermal potential but few identified geothermal systems include northeastern Nevada, western Utah, southern Idaho, eastern Oregon, and parts of New Mexico and Colorado.

Enhanced Geothermal Systems

Conventional geothermal resources depend on hydrothermal fluid circulation that arises only with the convergence of high temperatures—due either to magmatism or other tectonic processes that elevate temperature gradients in the Earth's crust—and permeability, typically fracture permeability produced as a result of active faulting (Duffield and Sass, 2003). Enhanced Geothermal Systems (EGS) are geothermal resources that require some form of engineering to develop the permeability necessary for the circulation of hot water or steam and the recovery of heat for electrical power generation. Because exploitation of EGS resources incorporates the augmentation or creation of permeability in place, the presence of elevated temperatures at drillable depths is the dominant factor controlling the quality of the resource.

Under the assumption of continued successful implementation of EGS technology, models for the extension of geothermal energy recovery techniques into regions of hot but low permeability crust yield an estimated mean electric power resource on private and accessible public land of 517,800 MWe (table 1), with a 95% probability of 345,100 MWe and a 5% probability of 727,900 MWe. This is approximately half of the current installed electric power generating capacity in the United States and an order of magnitude larger than the conventional geothermal resource. This estimate does not include Alaska and Hawaii, because there is not enough information to accurately estimate crustal temperatures in those States on a regional basis. With EGS technology at an early stage of development (DOE, 2008), the assessment results should be considered provisional.

The high crustal heat flow favorable for EGS development is more uniformly distributed across the western United States, and this is reflected in the distribution of the resource among the states, as shown in figure 2*C*. The EGS resource distribution, although large in total magnitude, is also relatively diffuse. In contrast to power production from conventional geothermal reservoirs, which is often concentrated at 10 to 20 MWe per km^2 of field area, the EGS resource outside of the high-temperature margins of

Table 1. Electric power generation potential in Megawatts-electric (MWe) from identified and undiscovered geothermal resources and Enhanced Geothermal Systems in the western United States.

[All electric power generation figures are calculated on a basis of 30 years of production. F95 represents a 95% chance of at least the amount tabulated; other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. N is the number of identified geothermal systems included in the estimate].

		Identified Resources (MWe)				Undiscovered Resources (MWe)				Enhanced Geothermal Systems (MWe)			
State	**N**	**F95**	**F50**	**Mean**	**F5**	**F95**	**F50**	**Mean**	**F5**	**F95**	**F50**	**Mean**	**F5**
Alaska	53	236	606	677	1,359	537	1,428	1,788	4,256	NA	NA	NA	NA
Arizona	2	4	20	26	70	238	775	1,043	2,751	33,000	52,900	54,700	82,200
California	45	2,422	5,140	5,404	9,282	3,256	9,532	11,340	25,439	32,300	47,100	48,100	67,600
Colorado	4	8	11	30	67	252	821	1,105	2,913	34,100	51,300	52,600	75,300
Hawaii	1	84	169	181	320	822	2,027	2,435	5,438	NA	NA	NA	NA
Idaho	36	81	283	333	760	427	1,391	1,872	4,937	47,500	66,700	67,900	92,300
Montana	7	15	51	59	130	176	573	771	2,033	9,000	16,100	16,900	27,500
Nevada	56	515	1,216	1,391	2,551	996	3,243	4,364	11,507	71,800	101,300	102,800	139,500
New Mexico	7	53	153	170	343	339	1,103	1,484	3,913	35,600	54,400	55,700	80,100
Oregon	29	163	485	540	1107	432	1,406	1,893	4,991	43,600	61,500	62,400	84,500
Utah	6	82	171	184	321	334	1,088	1,464	3,860	32,600	46,500	47,200	64,300
Washington	1	7	20	23	47	68	223	300	790	3,900	6,300	6,500	9,800
Wyoming	1	5	31	39	100	40	129	174	458	1,700	2,900	3,000	4,800
Total	248	3,675	8,356	9,057	16,457	7,917	23,739	30,033	73,286	345,100	507,000	517,800	727,900

identified geothermal systems averages approximately 0.5 MWe per km^2. However, continued advances in EGS technology, particularly with respect to creation of reservoirs at great depth and improved thermal energy recovery, could add substantially to the resource estimates (DOE, 2008).

EGS are not the only type of unconventional geothermal resource. Previous assessments (see for example, Muffler, 1979) indicated significant unconventional geothermal resource potential associated with fluids in deep sedimentary basins of the United States. These unconventional geothermal resources will be assessed in a future study.

Geothermal resources have the potential to play a much more significant role in our Nation's energy mix. This assessment of geothermal resources in the United States is only part of the USGS effort to help ensure our Nation's energy future.

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USGS Geothermal Resources Assessment Team—*Colin F. Williams, Marshall J. Reed, Robert H. Mariner, Jacob DeAngelo, S. Peter Galanis, Jr.*

Edited by James W. Hendley II
Graphic design by Jeanne DiLeo

For more information contact:
U.S. Geological Survey
Colin F. Williams: colin@usgs.gov,
345 Middlefield Road, Mail Stop 977
Menlo Park, CA 94025

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