OVERVIEW OF GEOTHERMAL TECHNOLOGIES

Introduction

Geothermal energy, the natural heat within the earth, arises from the ancient heat remaining in the Earth's core, from friction where continental plates slide beneath each other, and from the decay of radioactive elements that occur naturally in small amounts in all rocks.

For thousands of years, people have benefited from hot springs and steam vents, using them for bathing, cooking, and heating. During this century, technological advances have made it possible and economic to locate and drill into hydrothermal reservoirs, pipe the steam or hot water to the surface, and use the heat directly (for space heating, aquaculture, and industrial processes) or to convert the heat into electricity.

The amount of geothermal energy is enormous. Scientists estimate that just 1 percent of the heat contained in just the uppermost 10 kilometers of the earth's crust is equivalent to 500 times the energy contained in all of the earth's oil and gas resources [1].

Hydrothermal and Hot Dry Rock

This document characterizes electric power generation technology for two distinct categories of geothermal resources.

Hydrothermal resources are the "here-and-now" resources for commercial geothermal electricity production. They are relatively shallow (from a few hundred to about 3,000 meters). They contain hot water, steam, or a combination of the two. They are inherently permeable, which means that fluids can flow from one part of the reservoir to other parts of the reservoir, and into and from wells that penetrate the reservoir. In hydrothermal reservoirs, water descends to considerable depth in the crust, becomes heated and then rises buoyantly until it either becomes trapped beneath impermeable strata, forming a bounded reservoir, or reaches the surface as hot springs or steam vents. The water convects substantial amounts of heat from depths to relatively near the surface.

Hot Dry Rock (HDR) resources, on the other hand, are relatively deep masses of rock that contain little or no steam or water, and are not very permeable. They exist where geothermal gradients (the vertical profile of changing temperature) are well above average (>50^{o}C/km). The rock temperature reaches commercial usefulness at depths of about 4,000 meters or more. To exploit hot dry rock, a permeable reservoir must be created by hydraulic fracturing, and water from the surface must be pumped through the fractures to extract heat from the rock.

There are both strong similarities and large differences between hydrothermal and HDR geothermal resources and exploitation systems. Most of the component technologies, i.e., the power plant and well drilling methods, are very similar for both systems. The most important differences are that: (a) Hydrothermal systems are commercial today, while HDR systems are not, whereas (b) HDR resources are enormously larger (between 3,170,000 EJ and 17,940,000 EJ of accessible energy in the U.S.) than hydrothermal resources (on the order of 1,060 EJ to 5,300 EJ of accessible energy) [2]. By way of comparison, in 1995 the U.S. used about 95 EJ of primary energy. U.S. hydrothermal sources could supply that amount for 10 to 50 years. But U.S. Hot Dry Rock resources could supply that amount for somewhere between 30,000 and 500,000 years.

Because of these differences, the general strategic approach of national geothermal R&D programs (including that of the U.S.) has been to try to lower costs in the hydrothermal commercial arena today and, by so doing, to improve generic "geothermal" technology enough to make HDR exploitation economically feasible in the not-too-distant future.

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Hydrothermal Features

Hydrothermal resources are categorized as dry steam (vapor dominated) or hot water resources, depending on the predominant phase of the fluid in the reservoir. Although the technology is similar for both, dry steam technology is not included in this Technology Characterization because dry steam resources are relatively rare. Hot water resources are further categorized as being high temperature (>200°C/392°F), moderate temperature (between 100°C/212°F and 200°C/392°F), and low temperature (<100°C/212°F). Only the high and moderate temperature resources are adequate for commercial power generation.

Two separate power generation technologies, flash and binary, are characterized. The boiling temperature of water depends on its pressure, so as the pressure of the high temperature geothermal fluid is lowered in the plant, a portion (about 10 to 20% of it, depending on temperature and pressure) "flashes" to steam, which is used to drive a turbine to produce electricity. For moderate temperature resources, binary technology is more efficient. It is termed "binary" because the heat is transferred from the geothermal fluid to a secondary working fluid with a lower boiling temperature than water. The secondary fluid, vaporized by the heat, drives the turbine.

Beginning commercially in the 1950s, hydrothermal electric power generation has grown into an active and healthy, albeit not large, industry. About 7,000 MW of electric generation capacity have been developed worldwide, including about 2,800 MW in the U.S. [3]. Supply and demand forces and anticipated restructuring in the U.S. electric markets have resulted in very low demand for new geothermal capacity since 1990. However, geothermal energy is competing very well in markets outside the U.S., especially in Indonesia and the Philippines, where demand is high, geothermal resources are plentiful, and government policy is favorable. Approximately 2,000 additional MW will likely be developed worldwide in 1996 through 2000, with the majority of this being in Asia.

Hot Dry Rock Features

Flash or binary technology could be used with HDR resources depending on the temperature. However, because of the constraints imposed by high well costs, a larger portion of the accessible HDR resource will produce well-head fluids in the moderate temperature range. Therefore, binary technology is characterized for HDR resources.

To date, HDR resources have not been developed commercially for two reasons. Well costs increase exponentially with depth, and since HDR resources are much deeper than hydrothermal resources, they are much more expensive to develop. Also, although the technical feasibility of creating HDR reservoirs has been demonstrated at experimental sites in the U.S., Europe, and Japan, operational uncertainties regarding impedance (resistance of the reservoir to flow), thermal drawdown over time, and water loss make commercial development too risky.

Resource Details

In the U.S., the higher quality geothermal resources (both hydrothermal and HDR) are predominately located in the western states, including Alaska and Hawaii, as shown in the map below. Development of hydrothermal resources for electric power generation has been limited to California, Nevada, Utah, and Hawaii. Most of the western U.S. contains HDR resources, with the highest grade resources probably located in California and Nevada.

Scientists have made various estimates of the geothermal resource in the U.S. The U.S. Geologic Survey (USGS) completed the nation's most comprehensive assessment of geothermal resources, documented in USGS Circular 790, published in 1978 [2]. Circular 790 estimated the known, accessible hydrothermal resource to be about 23,000 MW

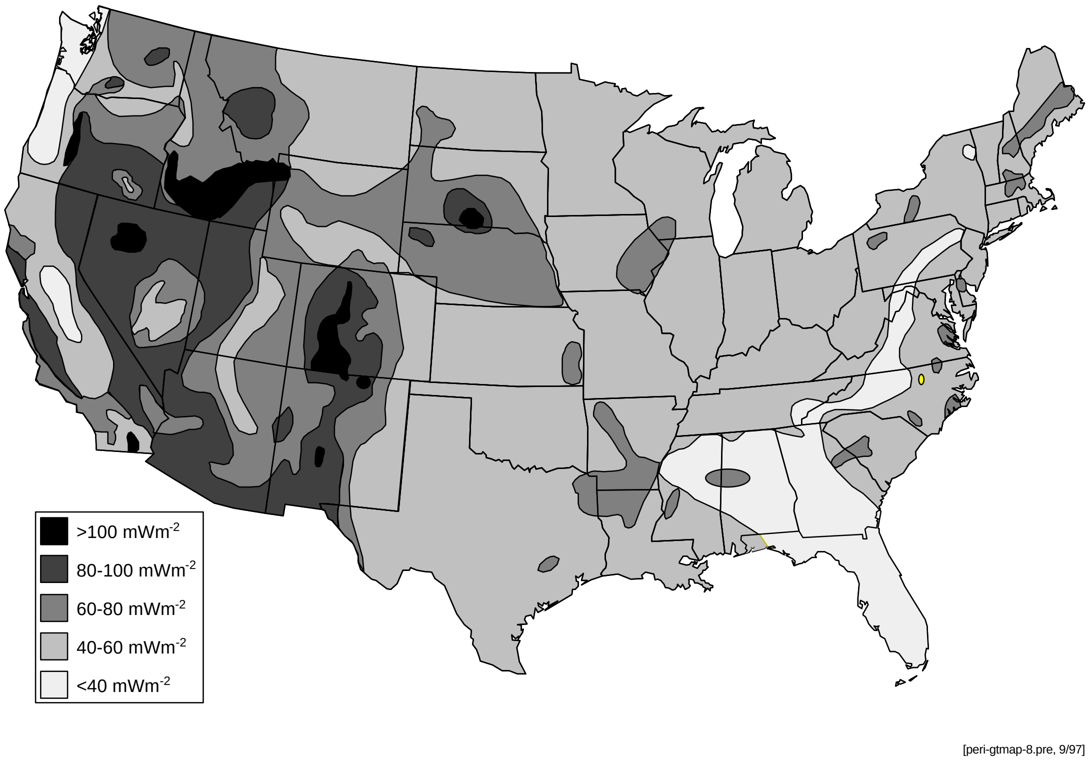

Figure 1. Geothermal resource quality in the United States.

of electric capacity for 30 years, and the as yet undiscovered accessible hydrothermal resource to be 95,000 to 150,000 MW of electric capacity for 30 years. It should be noted that the accessible resource is that which is accessible with current technology, but not necessarily economic. Considerable geothermal exploration and development in the U.S. since the mid 1950s has identified and characterized (moderately well) about 3,000 to 5,000 MW of hot water hydrothermal resources. Exploration work in the Cascade Mountains of Oregon in the 1990s seems to preclude the existence of the significant hydrothermal resource once estimated for that area.

An unpublished study by the University of Utah Research Institute in 1991 estimated about 5,000 MW of electric capacity for 30 years would be available at a cost of 5.5¢/kWh [4]. Recent preliminary analyses by the authors of the geothermal TCs suggest that for Hydrothermal electricity in 1997, no capacity would be available at ≤2¢/kWh, about 5,000 MW would be available at ≤3¢/kWh, and about 10,000 MW available at ≤5¢/kWh. If the predicted technology improvements for 2020 hold true, then 6,000 MW would be available at ≤2¢/kWh, about 10,000 MW available at ≤3¢/kWh, and about 19,000 MW available at ≤5¢/kWh. (These prices are levelized in constant dollars, using the "GenCo" financing assumptions described in Chapter 7.) Also note that the lowest prices given here are lower than the price calculated for the characterized geothermal flash power plant because the characterized plant is for a "typical" rather than "least expensive" geothermal high-temperature reservoir.

Although the potential of the nation's HDR resource has been studied less and is less well understood, it is believed to be very much larger than that of the hydrothermal resource. Tester and Herzog estimated the U.S. high grade HDR resource to have the potential of generating 2,800,000 MW at a cost ≤8.7¢/kWh (1996$) using 1990 technology [5]. For the year 2020 technology projected in the Hot Dry Rock TC, the current authors estimate that about 2,000,000 MW would be available from very high quality resource regions at ≤5¢/kWh, and that as much as 17,000,000 MW (about

24 times the current installed electric capacity in the U.S.) of HDR would be available at $\leq$6¢/kWh. (The economic assumptions here are the same as stated in the paragraph above.)

Aspects of Cost Estimates

The current state of many aspects of geothermal technology is fairly well documented. Indeed, the timing of this characterization of geothermal technologies is opportune in that it follows the first major engineering analysis of the cost and performance of geothermal power plants in 15 years. The "Next Generation Geothermal Power Plants" study (NGGPP), published in 1996, characterizes current flash and binary technology and evaluates new technologies proposed for the next generation of geothermal power plants [6]. Prior to this study, it has been difficult to obtain current cost and performance data for geothermal power plants because of the proprietary nature of this information.

The Hydrothermal and Hot Dry Rock TCs incorporate much data from the NGGPP. However, the characterization of Hydrothermal Flash reflects decreased flash plant capital costs (approximately 40% less than those documented in the NGGPP) due to intense competition. As of mid-1997, capital costs for binary plants appear to have been unaffected by these factors.

The HDR technology characterization depends on the NGGPP for binary power plant cost and performance data. The NGGPP includes an analysis of HDR technology that some believe is too conservative. The current HDR characterization is based on a higher grade HDR resource than that in the NGGPP. The NGGPP HDR well cost (including fracturing) estimates were about 30% higher than the TC HDR well costs, which were estimated by an experienced geothermal drilling engineer based on the costs of deep geothermal wells drilled recently in Nevada. The costs of creating the HDR reservoir, as well as its performance, are based on estimates of HDR scientists at Los Alamos National Laboratory, where HDR has been studied for the last 20 years.

Projections of Technology Improvements

For geothermal, as for other renewable energy electric supply technologies, the "accuracy" of projections of improvements in cost effectiveness are very important because in many instances, use of the technologies at specific locations will not be cost effective until the technologies are improved somewhat. The projections for improvements in the cost and performance of hydrothermal and HDR technologies are a synthesis of what various experts believe is possible.

The projections for improvements in hydrothermal technology are based on trends in performance and cost since about 1985 when U.S. firms first started constructing many hydrothermal power systems. It has been apparent that for both wells and power plants, the earliest forms of the technologies -- borrowed more or less wholly from other industries and uses -- have been constantly analyzed, rethought, and improved. The past five years especially have seen much new attention focused on how to improve the cost effectiveness of power plants, through changes in the underlying process cycles and conditions used to convert heat to electricity.

The single major exception to this ten-year (1985-1995) trend of apparent improvements has been in the area of industry's ability to locate and target, in many reservoirs, high-permeability zones for fluid collection and delivery. But here too, constant theoretical progress is being made, that is soon likely to engender practical progress.

The estimates for current and projected HDR cost and performance are more speculative than those for hydrothermal technology since HDR technology is much less mature and has not been applied commercially. Therefore, there is greater uncertainty in the HDR technology estimates. With HDR technology, the stated estimates are for the best cost and performance that is reasonably possible; the estimated uncertainty values reflect the possibility of lower performance and less improvement in the technology.

The projections are predicated on various assumptions about factors that will affect the timing and extent of improvements in the technologies. These include the levels of funding for hydrothermal and HDR R&D in several countries, as well as fossil fuel drilling and well completion R&D, supply and demand in electricity markets, supply and demand in petroleum markets (this greatly influences drilling costs and private funding of drilling research), public policy (especially regarding energy and the environment) in several countries, currency fluctuations, and technological progress in other electric supply technologies.

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