PROCEEDINGS, Thirty-Fifth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 1-3, 2010
SGP-TR-188

FUTURE OF GEOTHERMAL ENERGY

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ABSTRACT

This paper first describes the salient features of the various types of geothermal energy resources potentially available for exploitation: (1) convective ("hydrothermal") systems, (2) enhanced geothermal systems ("EGS"), (3) conductive sedimentary systems, (4) produced water from oil and gas fields, (5) geopressured systems, and (6) magma energy. Of these six types, only hydrothermal systems have been commercially exploited to date; there are still technical or economic barriers to exploiting the others. In the U.S., the resource base in EGS is two orders of magnitude higher than in the other types combined; the same is likely to be true for the world.

The paper then considers how long geothermal energy can supply the U.S. and the world. It can be argued that commercial geothermal energy exploitation is primarily a heat mining operation rather than tapping an instantly renewable energy source, such as, solar, wind or biomass energy. At the current annual energy consumption rate, geothermal heat mining can theoretically supply the world for several millenia. If a commercial geothermal exploitation project is operated for a typical life of 20 to 30 years and then shut down, the resource would be naturally replenished and available for exploitation again in about a century. With such a scheme, a geothermal project could be made entirely renewable, and therefore, practically inexhaustible. This situation is comparable to sustainable forestry.

Finally, the paper considers the potential rate of growth in installed geothermal power capacity. It is concluded that between years 2010 and 2050, geothermal power capacity in the world would increase from 10,000 MW to perhaps as high as 58,000 MW. The rate of growth in power capacity could be higher if adequate commercial incentives are offered by governments and international agencies.

INTRODUCTION

Figure 1 is a map of the world showing the location of the "Ring of Fire", along which active volcanoes are common and earthquakes occur frequently. This Ring of Fire is defined by the boundaries of "tectonic plates" that form the earth's crust. About 10,000 MW of commercial geothermal power capacity developed worldwide to date is situated nearly exclusively within this ring. However, geothermal power capacity can be and has been developed outside this ring. Furthermore, several different types of geothermal energy resources can be exploited to produce electric power. Fundamentally, two types of geothermal systems can be defined: conductive and convective (Figure 2). In a conductive geothermal system, temperature in the subsurface increases linearly with depth due to conductive heat flow vertically upward. In a convective geothermal system, temperature remains nearly constant with depth, signifying heat flow primarily by fluid convection. Typically an impermeable "cap rock" layer contains the convective system and defines its top.

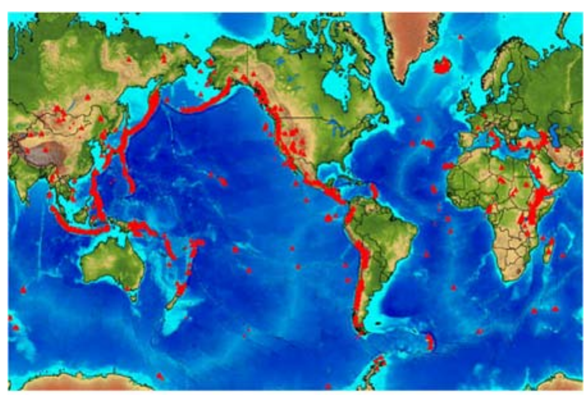


Figure 1: The Ring of Fire

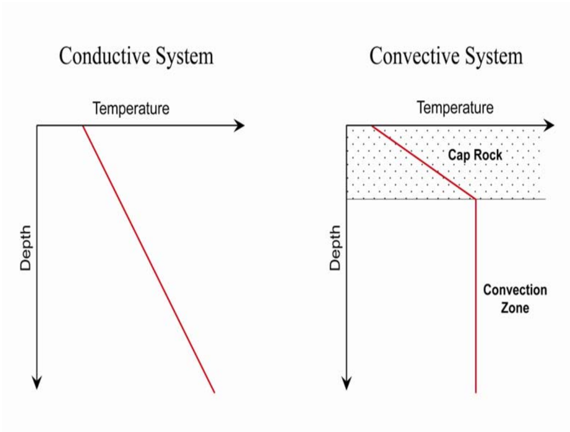


Figure 2: A Matter of Definition

TYPES OF GEOTHERMAL SYSTEMS

Several different types of geothermal systems can be exploited: (a) convective (or so called hydrothermal) systems, (b) enhanced geothermal systems ("EGS"), (c) conductive sedimentary systems, (d) hot water produced from oil and gas fields, (e) geopressured systems, and (f) magma bodies.

Convective hydrothermal systems have seen several decades of commercial exploitation for electric power generation in about two dozen countries to date, but their distribution worldwide is limited. There are two basic classes of these convective systems depending on the source of the thermal energy: volcanic and non-volcanic. A volcanic convective system drives its thermal energy from a convecting magma body, while a non-convective system drives its thermal energy from meteoric water that has heated up by deep circulation in high heat flow areas of the earth; there is no magma body associated with such a system. The installed power capacity that exploits such systems totals about 10,000 MW worldwide and 3,000 MW in the U.S. The reserve base in such systems in the U.S. is estimated to be in the 10,000 to 30,000 MW range (U.S.G.S., 2009).

Figure 3 presents a cross-sectional view of the temperature distribution in such a system (Beowawe geothermal field in Nevada, USA) that is non-volcanic; this figure graphically illustrates the occurrence of a convective "plume" of hot water rising diagonally from depth towards the surface.

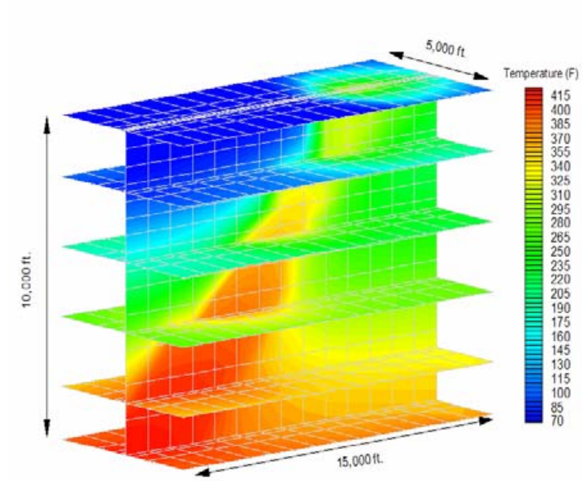


Figure 3: Beowawe Geothermal Field – Initial State Temperature Distribution (From Butler, et al, 2001)

It has been suggested (Stefansson, 2005) that a positive correlation exists between the geothermal resource base potentially available from convective systems of the volcanic type in a country and the number of active volcanoes in the country (Table 1). Even if a country does not have active volcanoes, an exploitable geothermal resource base may exist in the form of non-volcanic convective systems. For example, Figure 4 shows the cumulative frequency of the number of convective geothermal systems at various temperature levels in the United States identified in Muffler, et al, (1979). In Figure 4, the systems hotter than 200°C are generally volcanic while those cooler than 200°C are non-volcanic, the latter systems being more numerous than the former.

COUNTRY	NO. OF ACTIVE VOLCANOES	GEOTHERMAL RESOURCE BASE (MW)
U.S.A	133	23,000
Japan	100	20,000
Indonesia	126	16,000
Philippines	53	6,000
Mexico	35	6,000
Iceland	33	5,800
Nicaragua	20	4,350
New Zealand	19	3,650

Table 1: Number of Active Volcanoes in a Country and the Geothermal Resource Base

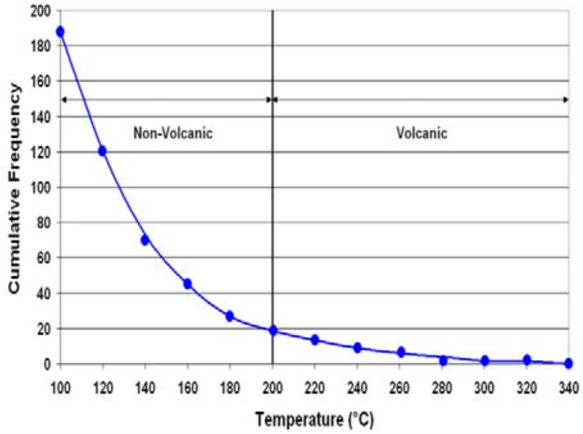


Figure 4: Cumulative Frequency versus Temperature of Identified Geothermal Fields in the United States (as of 1978)

An enhanced geothermal system implies a man-made reservoir created by hydrofracturing impermeable or very "tight" rock through wells. By injecting normal temperature water in a well in such an artificially-fractured reservoir and producing from another well, the water heated up by heat conduction from the rock it is possible to extract thermal energy. The EGS systems represent conductive systems that have been enhanced in their flow capacity and storage capacity by hydrofracturing. EGS can be developed, in theory, anywhere in the world by drilling deep enough to encounter a commercially attractive temperature level. However, the EGS technology is still experimental and poses a series of technical challenges, such as, (a) creating a pervasively fractured large rock volume, (b) securing commercially attractive well productivity, (c) minimizing the rate of cooling of the produced water with time, (d) minimizing the loss of the injected water through fractures, and (e) minimizing any induced seismicity.

Attempts are being made to develop geothermal projects in sedimentary basins with high heat flow; these systems are neither EGS nor convective systems (due to the presence of impermeable shale layers preventing convection). No fracturing is generally needed for such systems because sedimentary rocks have intrinsic porosity and permeability. However, wells to exploit such systems may have to be very deep to ensure an adequate temperature level and well productivity may not prove adequate. No such systems have been commercially exploited to date, but developing such systems should be feasible if the reservoir temperature and flow capacity are high enough. Figure 5 shows the estimated levelized power cost in (¢/kWh) versus reservoir temperature for a series of reservoir flow capacity ("kh") values (in millidarcy-ft) for a project in such a system (Sanyal and Butler, 2009). Figure 5 shows that the levelized power cost decreases with increasing reservoir temperature and flow capacity, the rate of this decrease being more sensitive to reservoir flow capacity at lower temperature levels.

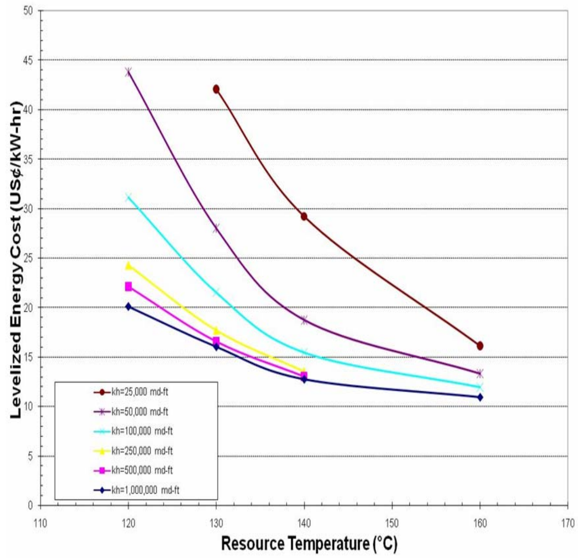


Figure 5: Levelized Energy Cost versus kh and Temperature (From Sanyal and Butler, 2009)

Another type of geothermal energy resource being considered for exploitation today is the heat contained in the water produced from deep oil and gas wells; the hot water may be co-produced with petroleum or from abandoned oil or gas wells. While there are no significant challenges to exploiting this energy resource, the cost of power from it may not be always attractive because of the relatively low temperature and low production rate of the water (Sanyal and Butler, 2009).

A type of geothermal energy resource of very restricted distribution worldwide is the "geopressured" systems. These are confined sedimentary reservoirs with pressures much higher than the local hydrostatic pressure. The high pressure in such systems may allow the exploitation of the kinetic energy of the produced water in addition to its thermal energy. Furthermore, because of its high pressure, such a system may contain attractive amounts of methane gas dissolved in the water; this gas may be used to generate electric power in a gas engine. Thus an ideal geopressured well can provide thermal, kinetic as well as gas-derived energy. No commercial geopressured project has been developed to date. There are several technical challenges to making this energy source commercial.

Exploitation of geothermal energy directly from a magma body is theoretically possible but faces many technical challenges. Moreover, the occurrence of magma bodies at economically drillable depths is uncommon.

POTENTIAL CONTRIBUTION OF GEOTHERMAL TO THE U.S. ENERGY NEED

Table 2 lists the estimates of the geothermal resource base (in Joule) up to a depth of 10 km in the U.S. for the various resource types (M.I.T., 2006). Table 2 also lists the number of years of supply, at the current U.S. energy demand level, the various types of geothermal resources can potentially offer.

Resource Type	Resource Base up to 10 km (J)	No. of Years of Potential Reserves
Convective	2.4E21 to 9.6 E21	~1
EGS	1.40E+25	1,400
Conductive Sedimentary	1.00E+23	10
Oil/Gas Field Waters	1.0E17 to 4.5E17	< 1
Geopressured	7.1E22 to 1.7E23	7 to 17
Magma Energy	7.40E+22	7

Table 2: U.S. Geothermal Resource Base (M.I.T., 2006)

This table clearly shows that other than EGS, geothermal resources offer a rather modest potential for contribution to the U.S. energy need for the long term. Figure 6 presents a plot of the approximate range of levelized power cost (in ¢/kWh) versus resource base (in kJ) for each of the potential geothermal resource types in the U.S. Figure 6 shows that oil-field (or gas-field) waters offer the cheapest source of electric power but represent a very small resource base, while EGS is a relatively expensive power source but has nearly two orders of magnitude higher resource base compared to all other geothermal resource types combined. Conventional geothermal systems and deep sedimentary geothermal systems, and possibly geopressured systems also, offer economic sources of power, but magma energy is clearly non-commercial today. The above estimates assume a geothermal resource base that is exhaustible at any given rate of exploitation. Yet, geothermal energy is considered a renewable resource. Therefore, we examine next this apparent contradiction.

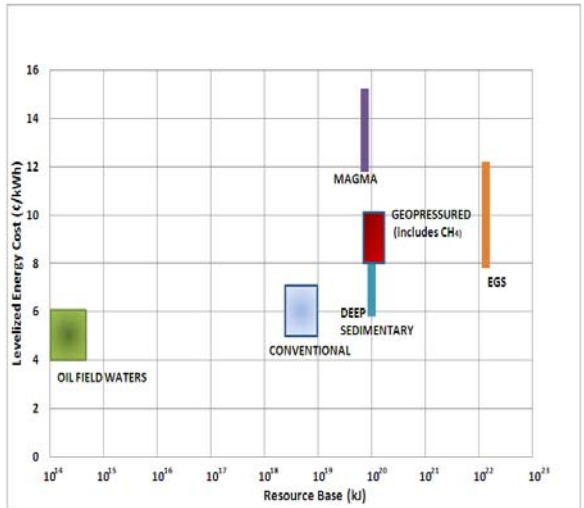


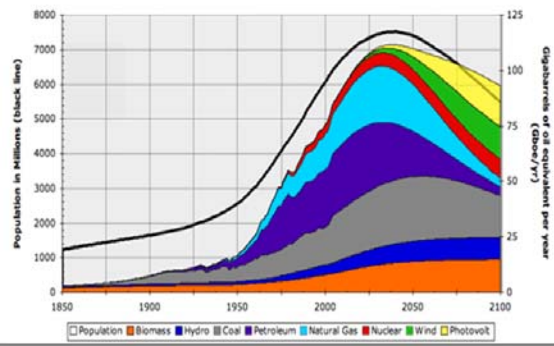
Figure 6: Resource Base and Power Cost of the Various Geothermal Energy Systems

RENEWABILITY OF GEOTHERMAL ENERGY

The ultimate source of geothermal energy is the extremely hot and molten core of the earth. Heat radiating out of the core is lost from the earth's surface, in the process giving rise to generally increasing temperature with depth. The energy contained in the earth's core is so vast as to be practically inexhaustible compared to mankind's energy demand. Geothermal energy would be instantly renewable if the energy extraction rate did not exceed the natural heat loss rate from the earth's surface, which happens to be of the same order of magnitude (about 10^{20}J per year) as the worldwide energy consumption rate today. However, the natural rate of heat loss per unit area of the earth's surface (on the order of 50 kW per square km) is so low that commercial geothermal energy extraction is primarily a case of "heat mining". The various types of geothermal energy sources considered earlier are essentially various alternative schemes of mining this heat, each with a relatively minor contribution from the renewable heat flow from the earth's core.

HOW LONG CAN GEOTHERMAL ENERGY SUPPLY THE WORLD?

The total amount of heat energy stored up to a depth of 5 km worldwide has been estimated at about 1.46 x 10^{26}J (Aldrich et al, 1981). A reasonable assumption is that on the order of 1% of this stored energy is "minable". If so, the recoverable resource base of geothermal energy worldwide up to a depth of 5 km is 1.46×10^{24}J. Therefore, at the current annual worldwide energy assumption rate of 4.18×10^{20}J, heat mining up to a depth of 5 km can theoretically supply the world's energy need for about 3,500 years (Johansson, 2005). This estimate can be considered conservative because even with today's technology, drilling to a depth of at least 10 km is technically feasible. Since temperature increases with depth, heat stored between the depths of 5 and 10 km should be higher than that from the surface to a depth of 5 km. Therefore, heat mining from the earth can theoretically supply the world at the present level of energy demand for many millennia. The above conclusion implicitly assumes that the world's energy need will not continue to increase indefinitely. This assumption is justified by the projection of world's population and energy demand by various parties (for example, Figure 7), which indicate that both the population and energy demand worldwide would peak by about the year 2050, after which both would start declining.



(From: The Quaker Economist, Vol. 7, No. 155 March 2007)

Figure 7: Forecast of World Population and Energy Production (from The Quaker Economist, Vol. 7, No. 155, March 2007)

Geothermal energy should be capable of supplying the world for a much longer period if heat mining is supplemented by exploiting the renewable aspect of geothermal energy. For example, if a geothermal energy exploitation project is operated for its typical amortization period of 30 years, and then shut down, the resource would be naturally and fully replenished in about a century (Pritchett, 1998), at which time it can be exploited all over again. With such an exploitation scheme, geothermal power can be considered truly renewable, and therefore, practically inexhaustible.

GROWTH TREND IN INSTALLED GEOTHERMAL POWER CAPACITY

Figure 8 (after Bertani, 2005) shows the installed capacity of geothermal power (MW) worldwide as a function of time since 1975. As Figure 8 shows, during the "energy crisis" period of 1975 - 1980, geothermal power capacity grew at an annual rate of 517 MW per year. Following the easing of the energy crisis after 1980, the annual growth in geothermal power capacity slowed to 202 MW per year for the next quarter century. Then after 2005, the most recent energy crisis ensued and triggered a faster growth rate in geothermal capacity of 413 MW per year. The growth is likely to accelerate more in the foreseeable future because of the increasing growth in power demand as well as the mounting pressure to increase the renewable energy component of the commercial power capacity worldwide.

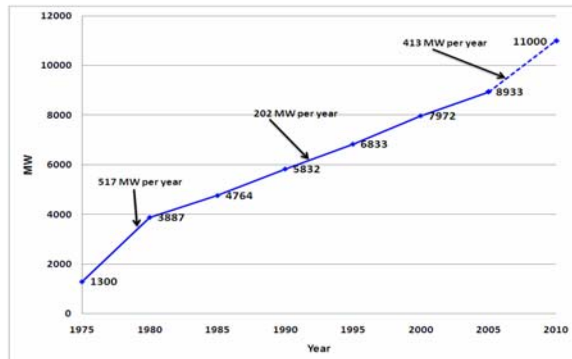


Figure 8: Worldwide Installed Geothermal Power Capacity (after Bertani, 2005)

Based on the trend discussed above, one could speculate on the possible trends of growth in geothermal power capacity worldwide as shown in Figure 9. The most pessimistic projection for future growth rate can be considered the twenty five-year trend of 202 MW per year seen between 1980 and 2005; with this trend, the installed capacity would reach about 20,000 MW by 2050. A more reasonable assumption for future growth rate may be 413 MW per year seen over the last 5 years. This assumption

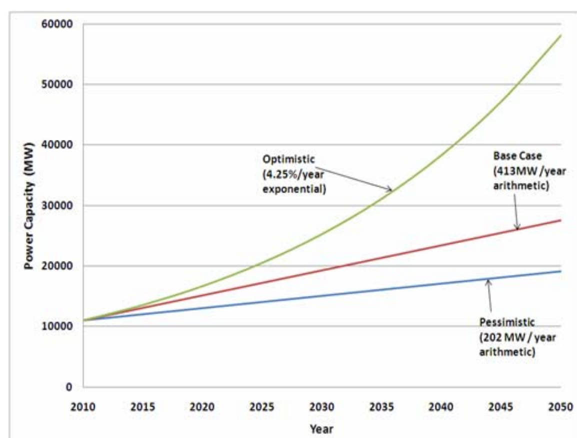


Figure 9: Possible Growth Trends in Worldwide Geothermal Power Capacity

(the "base case") indicates the prospect of an installed capacity of 28,000 MW by 2050. However, it is likely that there would be continuous acceleration in the rate of growth of geothermal power capacity over the next few decades. The recent increase in installed capacity from 8,933 to nearly 11,000 MW between 2005 and 2010 can be represented as an exponential growth rate of 4.25% per year. If this exponential growth rate were to continue over the next few decades, an installed power capacity of 58,000 MW would be reached by 2050 (Figure 9). Obviously, the rate of growth over the next few decades can be even higher if adequate commercial incentives are offered by governments and international agencies. The ultimate level of the power capacity achievable will also depend on the extent to which the EGS technology can be commercialized, for the other types of geothermal energy resources offer a much smaller resource base over the long term.

CONCLUSIONS

1. Of the six basic types of geothermal energy, the resource base in U.S. enhanced geothermal systems is two orders of magnitude higher than in the other types combined; the same is likely to be true for the world.

2. Commercial geothermal energy exploitation is primarily a heat mining operation rather than tapping an instantly renewable energy source, such as, solar, wind or biomass energy.

3. At the current annual energy consumption rate, geothermal heat mining can theoretically supply the world for several millennia.

4. If a commercial geothermal exploitation project is operated for a typical life of 30 years and then shut down, the resource would be naturally replenished and available for exploitation again in about a century; with such a scheme a geothermal energy project could be made entirely renewable, and therefore, practically inexhaustible.

5. Between the years 2010 and 2050, geothermal power capacity in the world would increase from about 11,000 MW to perhaps as high as 58,000 MW.

6. Rate of growth in power capacity can be higher if adequate commercial incentives are offered by governments and international agencies.

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